PREDICTING ASPECTS OF WATER QUALITY FROM PHOSPHORUS MASS BUDGET MODELS AND ALGAL BIOASSAYS

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Predicting Aspects of Water Quality from Phosphorus Mass Budget Models and Algal Bioassays

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List of Symbols

A	area of lake, m^2
$\Delta\%A$	percent change in algal standing crop
J	yearly supply of substance m (or phosphorus) to the lake, g yr^{-1}
L	lakes areal loading rate of phosphorus of J/L, g P m^{-2} yr^{-1}
$\Delta\%L$	percent change in areal loading
L_{Dev}	loading rate resulting from development, g P m^{-2} yr^{-1}
L_{Max}	maximum acceptable loading rate, g P m^{-2} yr^{-1}
m_w	amount of substance in the lake, g
O	annual phosphorus output, g yr^{-1}
$[P]$	total phosphorus concentration, g P m^{-3} or as specified
$\Delta\%P$	percent change in phosphorus concentration
$[P_{If}]$	average yearly total phosphorus concentration in the inflow, g P m^{-3} or as specified
$[P_{LAn}]$	average yearly steady state concentration of total phosphorus in lake water, g P m^{-3} or as specified
$[P_{LSum}]$	average total phosphorus concentration in the summer, g P m^{-3} or as specified
$[P_{LWin}]$	average total phosphorus concentration in the winter, g P m^{-3} or as specified
$P_{Max}]$	maximum allowable total phosphorus concentration, g P m^{-3} or as specified
$[P_{Pred}]$	average steady-state total phosphorus concentration predicted from Equation 2, g P m^{-3}
Q	total annual discharge, m^3 yr^{-1}
R	retention coefficient, unitless
SA	surface area, m^2
V	lake volume, m^3
V_{adj}	adjusted lake volume, m^3
V_{Ice}	volume of ice cover, m^3
V_{Win}	winter volume, m^3
$\overline{z}$	mean depth, m
σ	sedimentation rate coefficient
ρ	flushing rate or Q/V, m^{-3} yr^{-1}
ρ_f	flushing rate of flushing layer, yr^{-1}

Introduction

I. Rationale for Studying Phosphorus

The primary purpose of this project was to study the applicability of phosphorus mass budget models to lakes in the Snowy Range of the Medicine Bow Mountains. Phosphorus in the form of phosphate is an important constituent in living matter. Often present in extremely small amounts, Hutchinson (1957) suggested a deficiency of phosphorus may be more likely to limit productivity of lakes in a region than a deficiency of any other material. Phosphorus, however, is not the only element that can be limiting; nitrogen and carbon are often considered as limiting nutrients. But based on data accumulated over a period of years many investigators feel that carbon and nitrogen ordinarily will not be limiting on a long-term basis (e.g. Schindler, 1974, 1975; Schindler and Fee, 1974; Parker, 1977). The major source of phosphorus is the watershed whereas for nitrogen and carbon not only is the watershed a major source but also the atmosphere. If phosphorus is in excess to carbon then algal growth will deplete the available carbon before phosphorus becomes limiting. However, as the carbon is reduced the partial pressure of CO_2 in the water is lowered and therefore additional CO_2 diffuses into the water from the atmosphere. This continued addition of carbon will eventually allow complete utilization of phosphorus and the latter will become a limiting resource (Schindler *et al.*, 1972; Vanderhoef *et al.*, 1972, 1974; Emerson *et al.* 1973; Schindler and Fee, 1974; Schindler, 1974, 1975; Emerson, 1975).

Likewise, if phosphorus is in excess compared to nitrogen, then when nitrogen is completely used nitrogen fixation can occur, produce more usable nitrogen, and hence phosphorus is depleted to limiting concentrations. There is evidence that when the N:P ratio is lowered nitrogen fixing algae will occur in a lake even though they were previously absent or rare (Flett, 1972; Huang *et al.*, 1973; Megard and Smith, 1974; Schindler, 1974, 1975; Schindler and Fee, 1974).

the basic equation being

$$\frac{dm_w}{dt} = J - \sigma\, m_w - \frac{Q}{V}\, m_w \qquad \text{eq. 1}$$

m_w = amount of substance in the lake
J^w = yearly supply of substance m to the lake (μg/yr)
σ = sedimentation rate coefficient (1/yr)
V = lake volume (m^3)

In 1975, Vollenweider modified his previous models to include the mean residence time of water in the lake to account for flushing rates. Assumptions the model is based on are 1) the loading, flusing and sedimentation rates are constant through time; 2) the nutrient is uniformly mixed throughout the lake; 3) discharge concentration is equivalent to the mean concentration of the lake and 4) sedimentation rate is proportional to the concentration of the substance in the water.

Dillon (1975) also developed a phosphorus model which related retention time and flushing rates to phosphorus concentration in the lake. He developed the model because Vollenweider's (1968, 1969) models predicted several Ontario lakes should have high phosphorus concentrations, while actually measured concentrations were low. Dillon's model assumes that in a steady state system the concentration of phosphorus in the lake is described by

$$[P_{LAn}] = \frac{L(1-R)}{\rho\, \bar{z}} \qquad \text{eq. 2}$$

$[P_{LAn}]$ = average steady state concentration of total phosphorus in lake water
L = lake's areal loading rate of phosphorus $gPm^{-1}yr$
$\bar{z}$ = mean depth (m)
R = retention coefficient (fraction of input not lost through the outflow)
ρ = flushing rate (annual discharge/lake volume)

The assumptions of this model are essentially the same as those for Vollenweider's (1975) model.

Patalas (1972) proposed a phosphorus model based on basin population and per capita rate of discharge. Because of the transient nature of people using lakes in our study area we felt the model was not applicable. However, in a different region

Parker (1977) suggests that if we want to predict the long-term changes in a lake's algal standing crop resulting from phosphorus enrichment via bioassays (e.g., Algal Assay Procedure-Bottle test; AAP-BT), we should use data from nitrogen plus phosphorus treatments. *Selenastrum capricornutum* is the bioassay test organism used in the AAP-BT, and it is not a nitrogen-fixer. Therefore, to ascertain potential long-term effects one cannot consider only lake water plus phosphorus or only lake water plus nitrogen treatments.

II. Phosphorus Mass Budget Models

Because phosphorus is probably the most important nutrient affecting the trophic state of a lake, and because it is the easiest to control, many investigators have attempted to use this nutrient in models to predict the trophic state of a lake. Sakamoto (1966) and Dillon and Rigler (1974) have demonstrated a linear relationship between chlorophyll and phosphorus in lakes from different geographical localities.

Carlson (1977), has developed a Trophic State Index (TSI), a single number representing the state of a lake. It can be calculated from data on secchi disc transparency, chlorophyll *a*, or total phosphorus. The TSI indicates lake trophic levels on a scale of 0 to 100, with each increase of 10 representing a doubling of algal biomass. A large number of individual lake classes are possible with his numerical classification. This avoids problems associated with the use of the traditional nomenclature of oligotrophic, mesotrophic and eutrophic, which are ill-defined in areas of overlap.

Until recently the most widely accepted model was the mean lake depth-phosphorus loading relationship described by Vollenweider (1968). Although widely used to predict the trophic status of a lake it was found inadequate by some investigators because it did not consider parameters such as flushing and sedimentation rates. He later (Vollenweider, 1969) improved his model with

of the country the model might be useful. Dillon and Kirchner (1975) demonstrated that the type of rock and the use the soil was undergoing (e.g. agriculture) affected the degree of phosphorus loading in a drainage basin and a formula was developed by Kirchner (1975) for evaluating the relationship between phosphorus export and drainage densities (total length of stream segment divided by drainage basin area). Complex models have been developed by Imboden (1974) and Snodgrass and O'Melia (1975). Imboden makes a distinction between the zone of photosynthesis and the zone of mineralization, which during stratification closely coincide with the epilimnion and hypolimnion respectively. Snodgrass and O'Melia not only consider stratification (summer) but also winter conditions. The main problem with the Imboden and Snodgrass and O'Melia models is that a large amount of data is necessary for their use. We chose not to employ them for this reason.

III. Management Considerations

Several characteristics of models that are important for management personnel to use them in determining the trophic status of lakes have been outlined by Shapiro (1975) and Garn and Parrott (1977). First, the model must be simple in form and the data obtained for manipulation of the model must be unequivocal (i.e. the data must not allow for value judgments). The model parameters must be few in numbers but realistic enough to serve its purpose. These characteristics eliminate models described by Patalas (1972), Imboden (1974) and Snodgrass and O'Melia (1975). The model must be usable anywhere and it must be understandable to the lay public and officials dealing with policy matters. The results from the model should have a high correlation with visible characteristics of the lake and the parameters used in the model should not be available only during brief periods of the year. The model should be sensitive enough to detect water quality trends and should be the most cost-effective technique available.

IV. Our Hypotheses and the Model Selected for Investigation

We proposed to test two null hypotheses: 1) current mass budget models of phosphorus do not accurately predict phosphorus concentrations in mountain lakes; and 2) it is not possible to predict what effect a given increase in nutrient input (e.g. from second homes or road building) will have on the chemical and biological water quality of lakes. In order to test the first hypothesis we selected Dillon's (1975) model. The criteria for selection were that it was relatively simple to use (i.e. does not entail a great deal of data collection or computer usage) and that the parameters (especially flushing rate) utilized in the model were represented in our lakes by a wide range in values. In general Dillon's model meets the characteristics described by Shapiro (1975) and Garn and Parrot (1977).

We felt it was necessary to test phosphorus mass budget models in the Snowy Range because some of the lakes receive a great deal of intensive use (fishing and camping) for a short period of time. The lakes often do not open up until the middle of June and by the time the middle of September arrives the area is too cold except for the hardiest of users. This means about six months of ice cover, six months of open water with about three months of recreational usage. In addition, some of the lakes are very shallow (i.e. two meters) and act like wide spots in streams. Therefore we felt that these lakes are unique compared to the temperate lakes where much of the modeling work has been conducted. If Dillon's model is applicable in the Snowy Range then it would be an excellent model for Forest Service personnel to consider using in decision-making processes.

V. Description of the Lakes Selected for Study

Our study area was located within the Snowy Range of the Medicine Bow Mountains. This range in southern Wyoming consists of 530,929 acres of lodgepole pine, Engelman spruce, ponderosa pine, Douglas fir, alpine fir, timber pine, cottonwood and aspen.

Grassy mountain meadows are interspersed between timbered regions and Hudsonian, Canadian and lower artic life is found in the area. The Snowy Range has been managed primarily for watershed protection, recreation, grazing, timber and wildlife habitat (Kanaly, 1973).

Five study lakes were selected based on the following criteria: size, probable flushing rate, degree of second home development and our ability to reach them in the winter months. Morphometric characteristics of each of the lakes are described below.

East Glacier Lake (Figure 1) is located in Albany County (R79, T16, S3) at an elevation of 10,750 ft. The area of the lake is 3.2 ha. The mean depth (2.4 m) is about one-third of the maximum depth (7m). Other morphometric data are presented in Figure 1. Thirty percent of the lake consists of shoal areas and the bottom is comprised of detritus and mud. The lake drains into Big Brooklyn Lake.

Big Brooklyn Lake (Figure 2) is also located in Albany County (R79, T16, S10) and covers 9.2 ha at an elevation of 10,550 ft. Its maximum depth of 12m is about four times the mean depth (3.24m). Additional morphometric data are presented in Figure 2. Approximately 65% of the lake is shoal. The bottom consists of boulder, gravel and sand (Kanaly, 1973).

The outlet of Big Brooklyn Lake flows into Little Brooklyn Lake (Figure 3), the latter being located in Albany County (R79, T16, S10) at an elevation of 10,350 ft. The lake has a surface area of 3.2 ha, a mean depth of 0.8m, and a maximum depth of 2m. Figure 3 and the morphometric data thereon were taken from the map of Royer (1960). Mud, silt, detritus and clay compose the bottom (Kanaly, 1973).

Unnamed Lake (Figure 4) is located south of Little Telephone Lake in Albany County (R79, T16, S10) at an elevation of 10,700 ft. This was the smallest lake we studied, having an area of only .08 ha. However, the maximum and mean depths (2.5m and 0.85m, respectively) were similar to those of Little Brooklyn and Towner Lakes. See

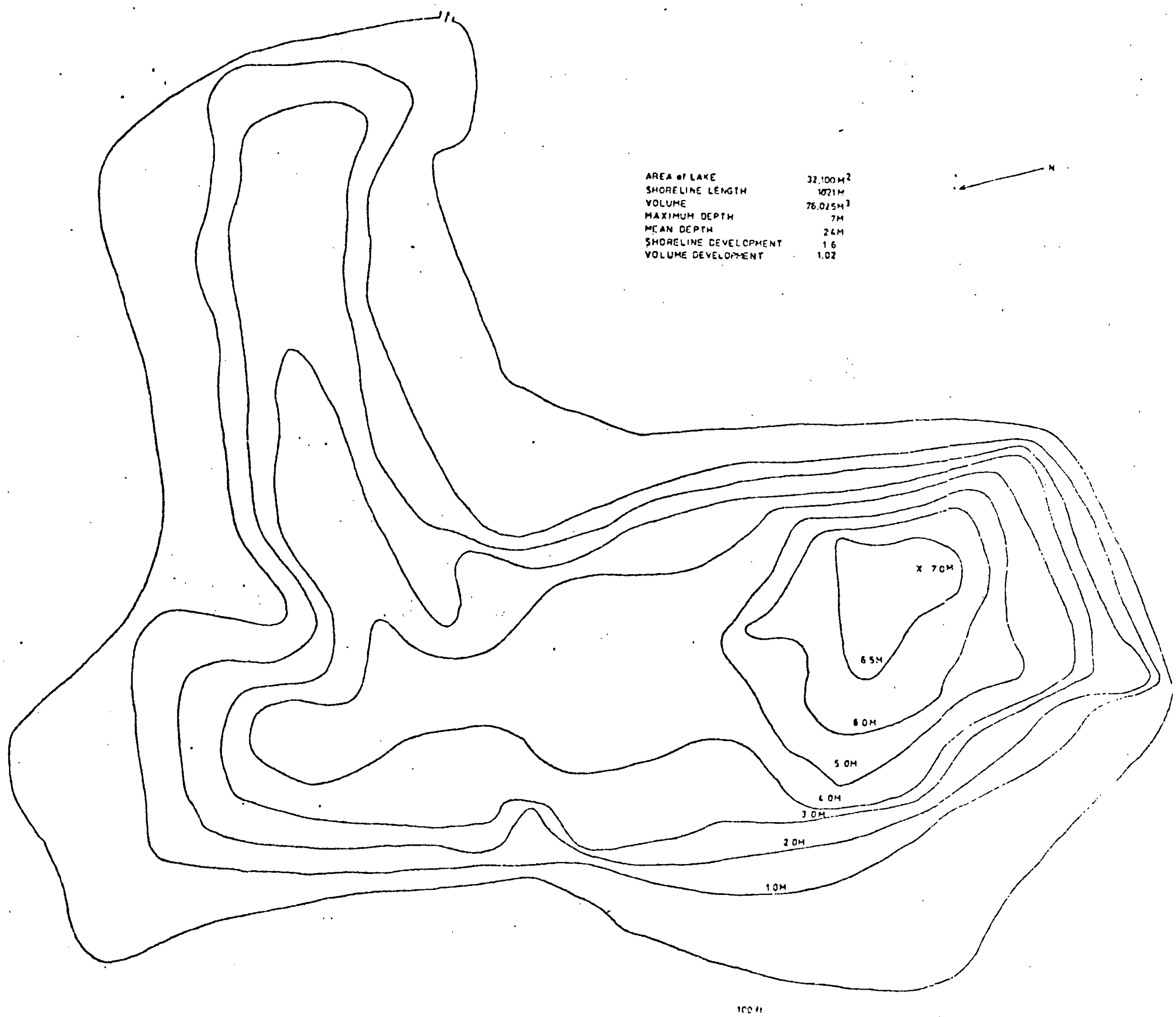


Figure 1. Morphometric map of East Glacier Lake.

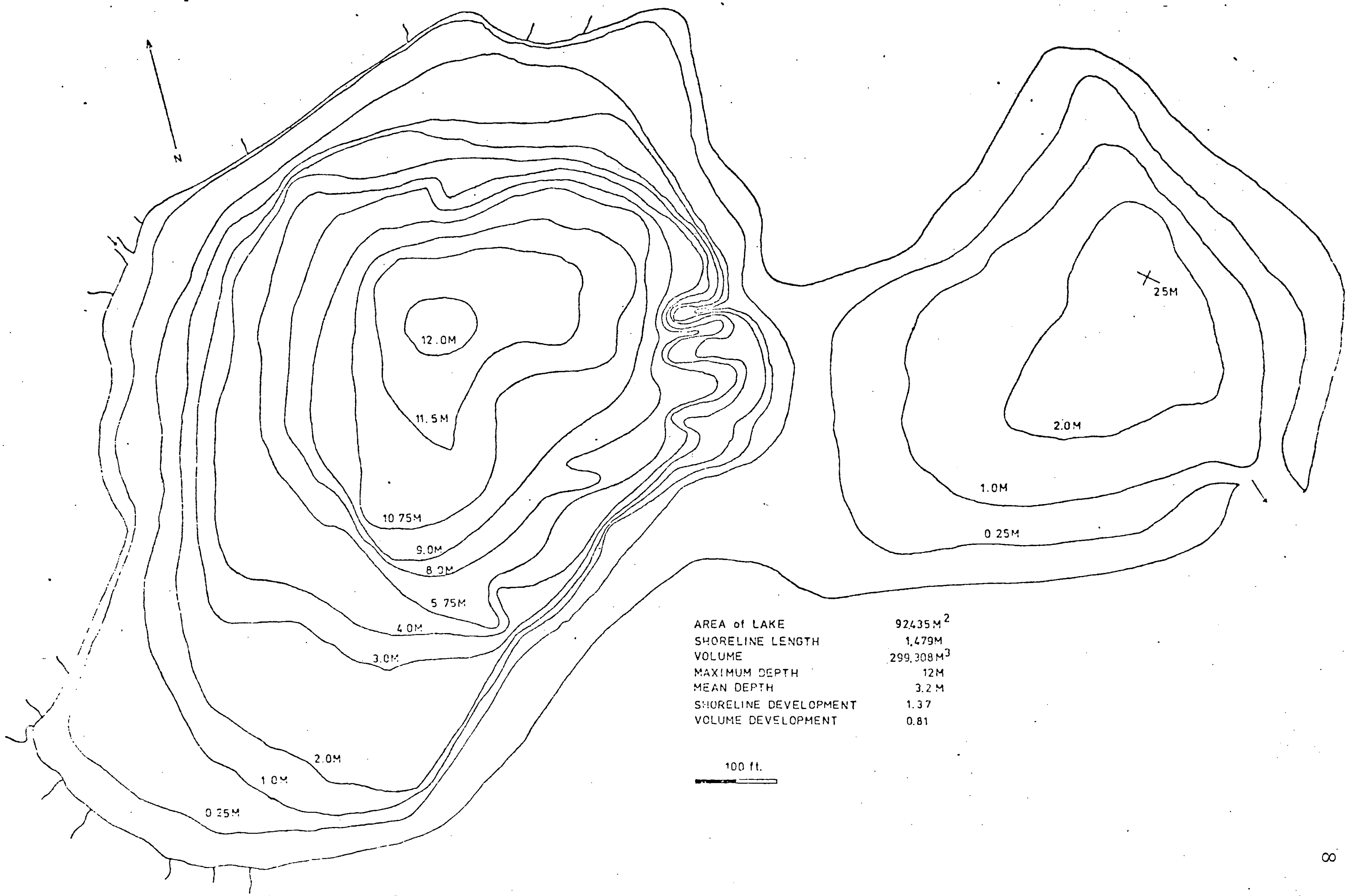


Figure 2. Morphometric map of Big Brooklyn Lake.

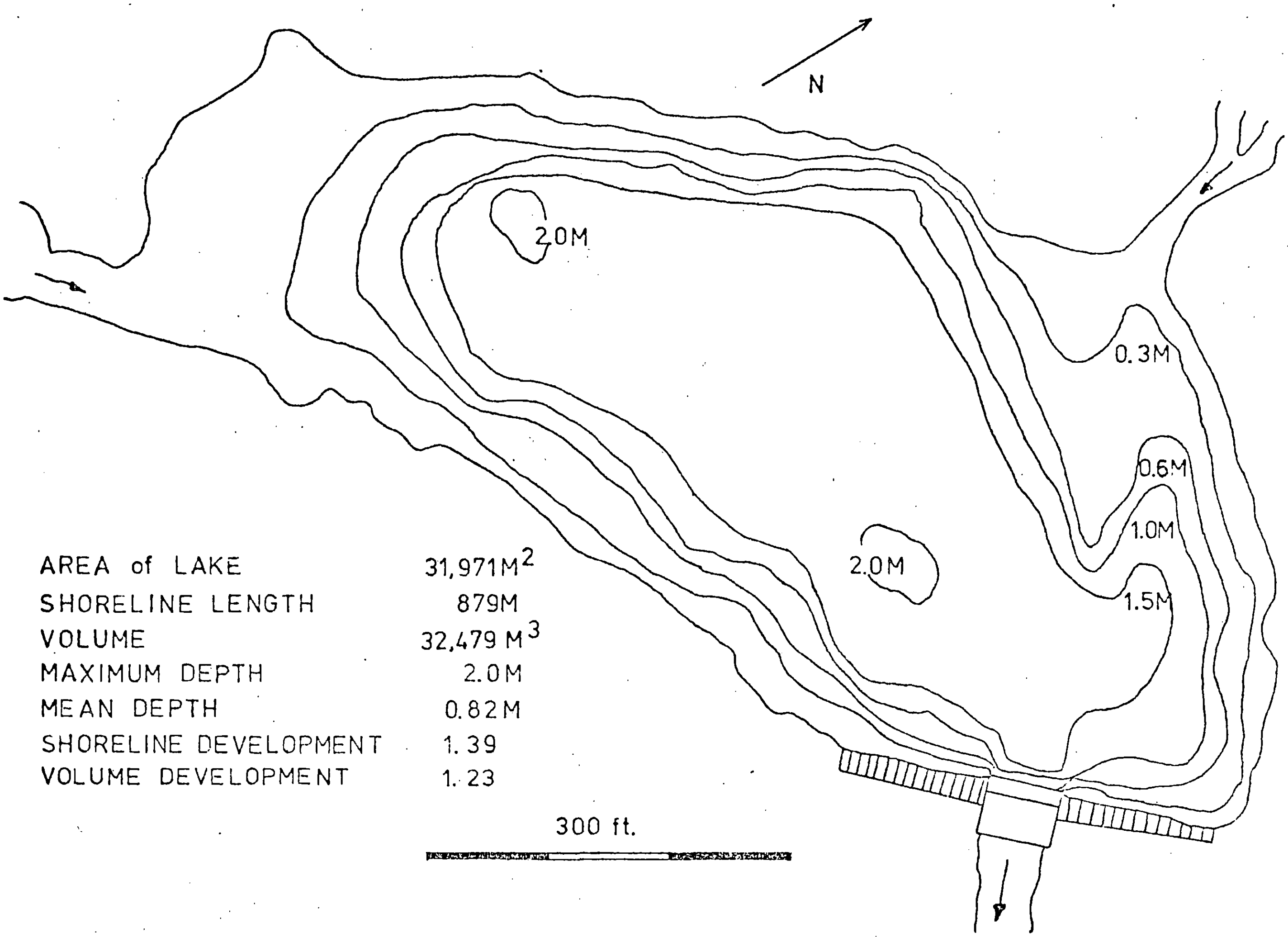


Figure 3. Morphometric map of Little Brooklyn Lake.

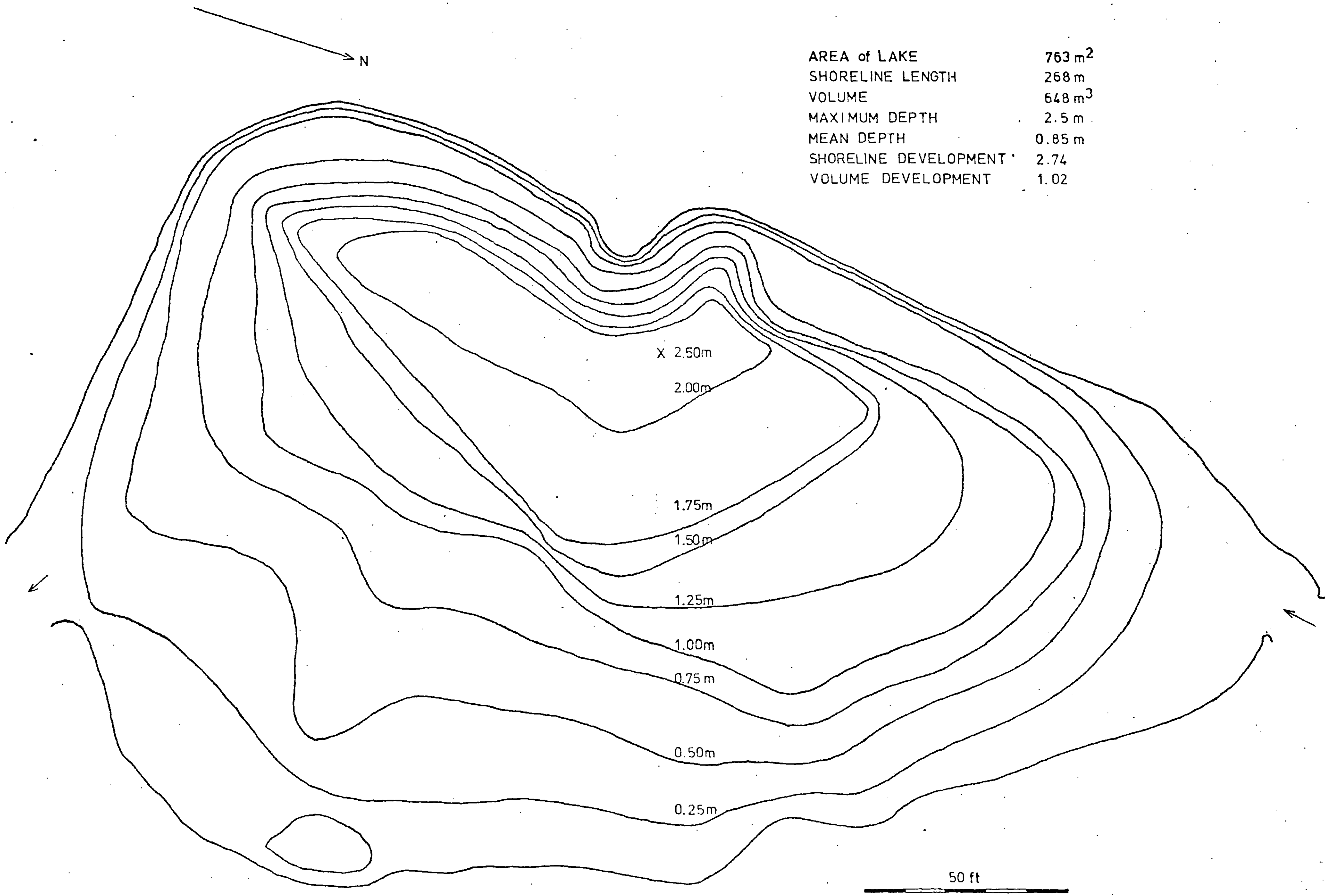


Figure 4. Morphometric map of Unnamed Lake.

Figure 4 for additional morphometric data. This lake's bottom is composed of boulders and gravel with some detritus.

The last lake we studied was Towner Lake, also located in Albany County (R79, T16, S15). The bottom consists of clay, mud, silt, and heavy vegetation (Kanaly, 1973). At an elevation of 10,487, this lake covers 3.6 ha with a maximum depth of 2.0m and a mean depth of 1.2m. Figure 5 is taken from Royer (1960): note that the figure presents additional morphometric data.

In addition to areal size, volume and depth differences, the lakes were represented by a wide range of flushing rates. As expected Big Brooklyn and East Glacier Lakes had the lowest flushing rates ($\rho = 6\ yr^{-1}$ and $\rho = 5\ yr^{-1}$, respectively) and the unnamed lake had the highest ($\rho = 2278\ yr^{-1}$). Intermediate values of ρ characterized Towner and Little Brooklyn Lakes which replaced their volumes 119 times and 116 times per year, respectively. The applicability of Dillon's model was investigated with data from four lakes. However, bioassays were performed on only two lakes, Towner and Big Brooklyn. These two lakes were chosen as representatives of their respective drainage systems and because they are the most likely of the five study lakes to experience increased recreational usage. Both are already developed with summer homes and, in the case of Big Brooklyn, a camp ground.

AREA of LAKE	35,612 m^2
SHORELINE LENGTH	846 m
VOLUME	44,944 m^3
MAXIMUM DEPTH	2.0 m
MEAN DEPTH	1.2 m
SHORELINE DEVELOPMENT	1.2
VOLUME DEVELOPMENT	1.8

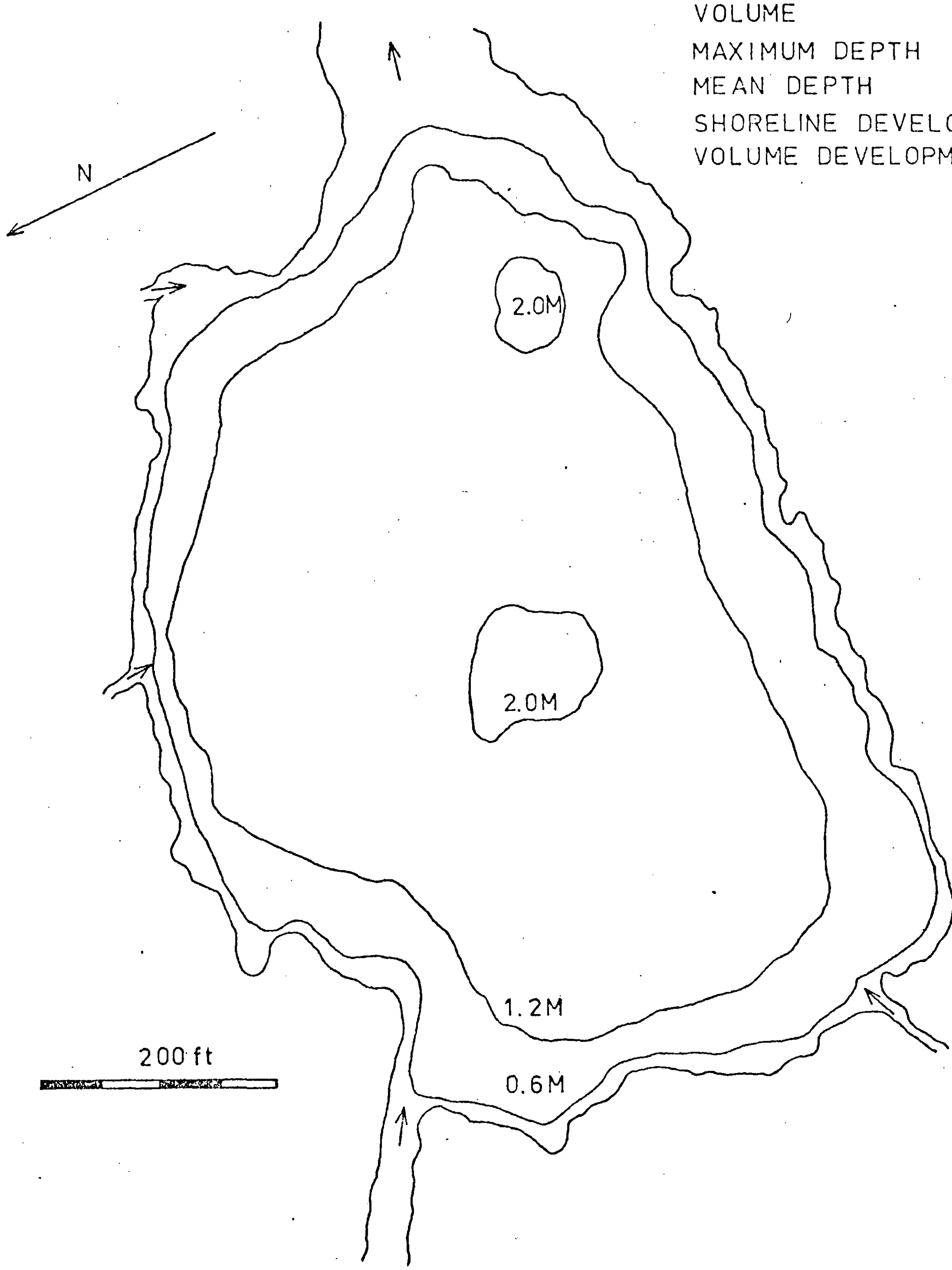


Figure 5. Morphometric map of Towner Lake.

Materials and Methods

Water samples were collected periodically for the analysis of total phosphorus. Samples from inlets and outlets were collected in polyethylene bottles. Lake water samples were taken at various depths with a Kemmerer sampler and transferred to polyethylene bottles.

Phosphorus determinations were performed in the laboratory on the same day as collection. Total phosphorus was analyzed as described by Eisenreich et al. (1975). This method employs persulfate-sulfuric acid digestion followed by development of a molybdenum blue color complex.

The velocity of water flow in inlets and outlets was estimated with a Gurley No. 625. Pygmy Current Meter. Sections of stream bed with relatively uniform contours were chosen, and velocities were measured at different depths on transects across the sections. Data on water velocity and cross-sectional area of stream were then used to calculate volume flow. Estimation by "eye" was used where volume flow was too small to permit the use of the current meter.

Immeasurable inflow (i.e. very small inlets, subterranean inflow and surface runoff) was estimated as the difference between total measurable inflow and measurable outflow, measurable outflow being greater than measurable inflow in most cases. Measurable inflow was greater than outflow in only a few instances. This probably represented error in measurement and was treated as such. Accordingly, when inflow was found to exceed outflow, the difference was split, half added to outflow and the other half subtracted from inflow so that inflow and outflow were treated as being equal.

Phosphorus input and output (mg sec^{-1}) were calculated by multiplying volume flows of inlets and outlets by phosphorus concentrations on the same dates. Where volume flow and phosphorus concentration were not measured on the same date linear interpolation of flow was used. Total phosphorus input to a lake on any given date was considered to be the sum of inputs from all inlets plus the input from

immeasurable sources. Immeasurable source input was estimated by multiplying immeasurable volume inflow by the mean of all phosphorus input concentrations on that date. These data were then graphed as total phosphorus input (mg sec^{-1}) versus date and as total phosphorus output versus date. The areas under the curves were integrated with a planimeter to calculate the average annual total phosphorus input and output per year, J (g yr^{-1}).

Lakes were mapped using the plane table and alidade method and soundings from a boat. Morphometric data were calculated according to the formulae of Hutchinson (1957). Data on Towner and Little Brooklyn Lakes were available from the literature (Royer, 1960).

Because of the nature of Dillon's model (Eq. 2) we decided that phosphorus data obtained from analysis of ice during the winter would not be useful. Likewise, water bound as ice was not flushed during winter months and was not included in flushing rate, ρ (yr^{-1}), calculations. Lake volume (V) was adjusted for ice volume (V_{ice}) as follows: Since lakes were ice covered approximately six months of the year, the adjusted lake volume (V_{adj}) was taken as an average of the ice-free volume and the volume of water under ice during the winter.

$$(V_{adj}) = \frac{V + (V - V_{ice})}{2} \qquad \text{eq. 3}$$

ρ (yr^{-1}) was then calculated as the annual discharge (m^3 yr^{-1}) divided by V_{adj} (m^3). Estimates of annual discharge were obtained by integrating curves of volume outflow versus date with a planimeter.

Areal phosphorus loading, L (g yr^{-1} m^{-2}), was calculated by dividing the total annual phosphorus input, J (g yr^{-1}), by the area of the lake, A (m^2). Retention coefficients, R, were estimated as the fraction of input not lost in the outflow (Dillon, 1975).

Average annual phosphorus concentrations in lakes were calculated as follows: Phosphorus concentrations at each depth (stratum) were graphed versus date (phosphorus in ice during the winter was not included). The curves were then divided into two sections, one representing six ice-free (summer) months and the other representing six winter months when lake volume was reduced by an amount equal to the volume of ice-cover. A six month average of 1m of ice was assumed. Integration of each section gave estimates of average phosphorus concentrations per stratum for the respective six month periods. Multiplying average summer phosphorus concentration in each stratum by respective stratum volumes yielded total phosphorus per stratum, the summation of which gave average total phosphorus in the lake (mg lake^{-1}) during the 6-month summer period. Average phosphorus concentration (mg l^{-1}) during the summer, $[P_{LSum}]$, was obtained by dividing average total summer phosphorus by V. Winter averages, $[P_{LWin}]$, were obtained in an analogous fashion except that average total winter phosphorus was divided by $(V - V_{ice})$. Average annual phosphorus concentration, $[P_{LAn}]$, was calculated as the arithmetic mean of $[P_{LSum}]$ plus $[P_{LWin}]$.

Algal bioassays were performed on water from Towner and Big Brooklyn Lakes using the Algal Assay Procedure-Bottle Test (EPA-1971) with Selenastrum capricornutum as a test organism. Water was collected from the surface of the lakes during summer (July 12 and August 2, 1977) and from beneath the ice in the winter (March 30 and May 17, 1977). Sample water was autoclaved and enriched with additions of nitrogen, phosphorus and combinations of nitrogen and phosphorus. Autoclaved lake water without nutrient additions was used as a control. Algal nutrient medium made up without nitrogen or phosphorus, but supplemented with varying amounts of nitrogen and phosphorus from the solutions used to enrich the lake water, was used as a technique check. Four replicates of each treatment were inoculated with Selenastrum. Algal standing crop was measured at various times during each bioassay by microscopically counting cells.

Results

A major distinction between East Glacier and the other lakes was that East Glacier lake did not have perennial, measurable inflow. Persistent inflow, if any, was apparently subterranean. It was therefore impossible to measure the phosphorus input to the Lake. In addition, snowpack made it difficult or impossible to measure outflow during the winter. For these reasons phosphorus input and output could not be calculated. Emphasis was placed on determining parameters necessary for the application of Dillon's model in the remaining four lakes, (Big Brooklyn, Little Brooklyn, Little Telephone and Towner).

A wide range of flushing rates resulted from hydrologic and mophometric differences between the remaining four lakes. Unnamed Lake had the largest flushing rate (2278 times yr^{-1}). In contrast Big Brooklyn replaced its volume only 6 times during 1976-77. Towner Lake and Little Brooklyn Lake had intermediate flushing rates of 119 times yr^{-1} and 116 times yr^{-1}, respectively.

Phosphorus concentrations in East Glacier Lake during the year ranged from 3.6 ppb to 17.6 ppb to 9.8 ppb and 3.4 ppb to 19.0 ppb respectively. (Fig. 6). $[P_{LAn}]$, $[P_{LSum}]$ and $[P_{LWin}]$ were all fairly similar, respectively being 10.1, 8.5, and 11.8 ppm (Table 2).

Phosphorus concentrations in Big Brooklyn ranged from 3.4 ppb to 48.0 ppb (Fig. 7) and from 3.0 ppb to 55.0 ppb in the inlets and outlets. As in East Glacier Lake $[P_{LAn}]$, $[P_{LSum}]$ and $[P_{LWin}]$ were not very different (10.1, 9.5 and 10.6 ppb respectively, Table 2).

Little Brooklyn Lake had phosphorus concentrations of about 13 ppb except under the ice in April, when 176.6 ppb was recorded (Fig. 8). Inlets and outlets ranged from 5.6 ppb to 24.8 ppb. Because of the high $[P_{LWin}]$ of 47.6 ppb, $[P_{IAn}]$ was much larger (30.5 ppb) than $[P_{LSum}]$ (13.4 ppb; Table 2).

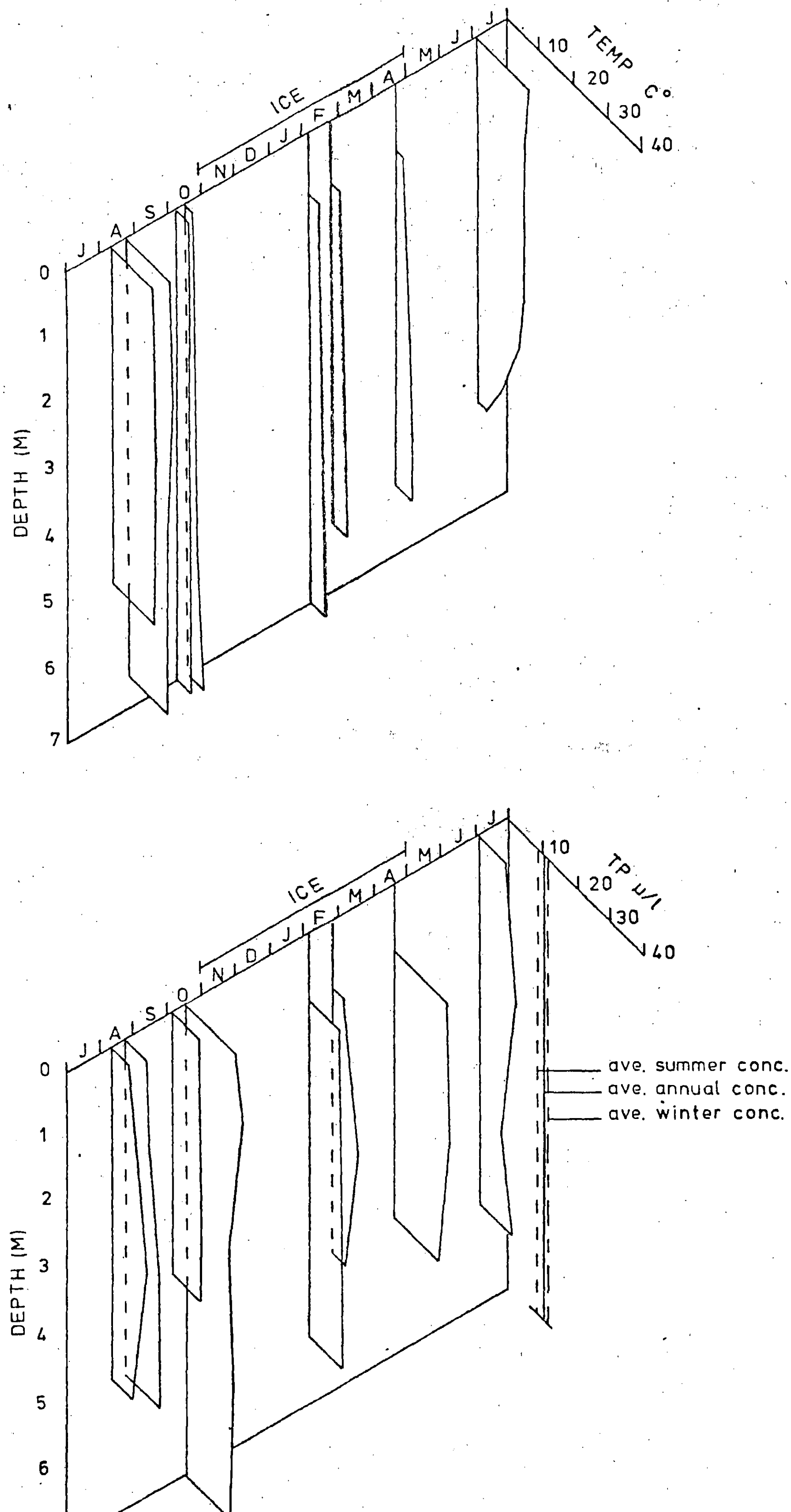
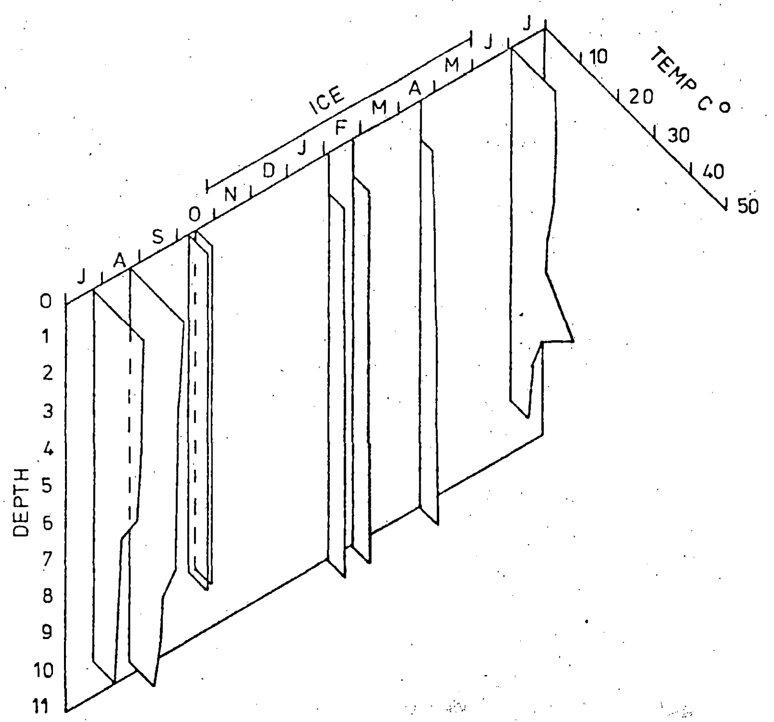


Figure 6. Data from East Glacier Lake on water temperature and total phosphorus, µg $liter^{-1}$. Note that the average phosphorus concentration calculated on an annual, summer and winter time scale is indicated on the TP axis ($[P_{LAn}]$, $[P_{LSum}]$, and $[P_{LWin}]$ respectively).



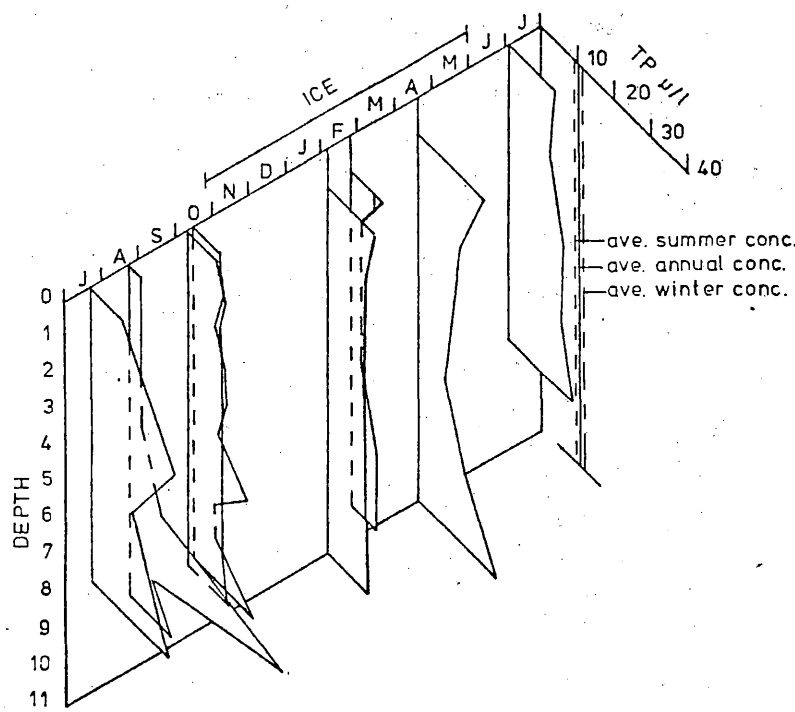


Figure 7. Data from Big Brooklyn Lake on water temperature and total phosphorus, µg liter^{-1}. Note that the average phosphorus concentration calculated on an annual, summer and winter time scale is indicated on the TP axis ($[P_{LAn}]$, $[P_{LSum}]$, and $[P_{LWin}]$ respectively).

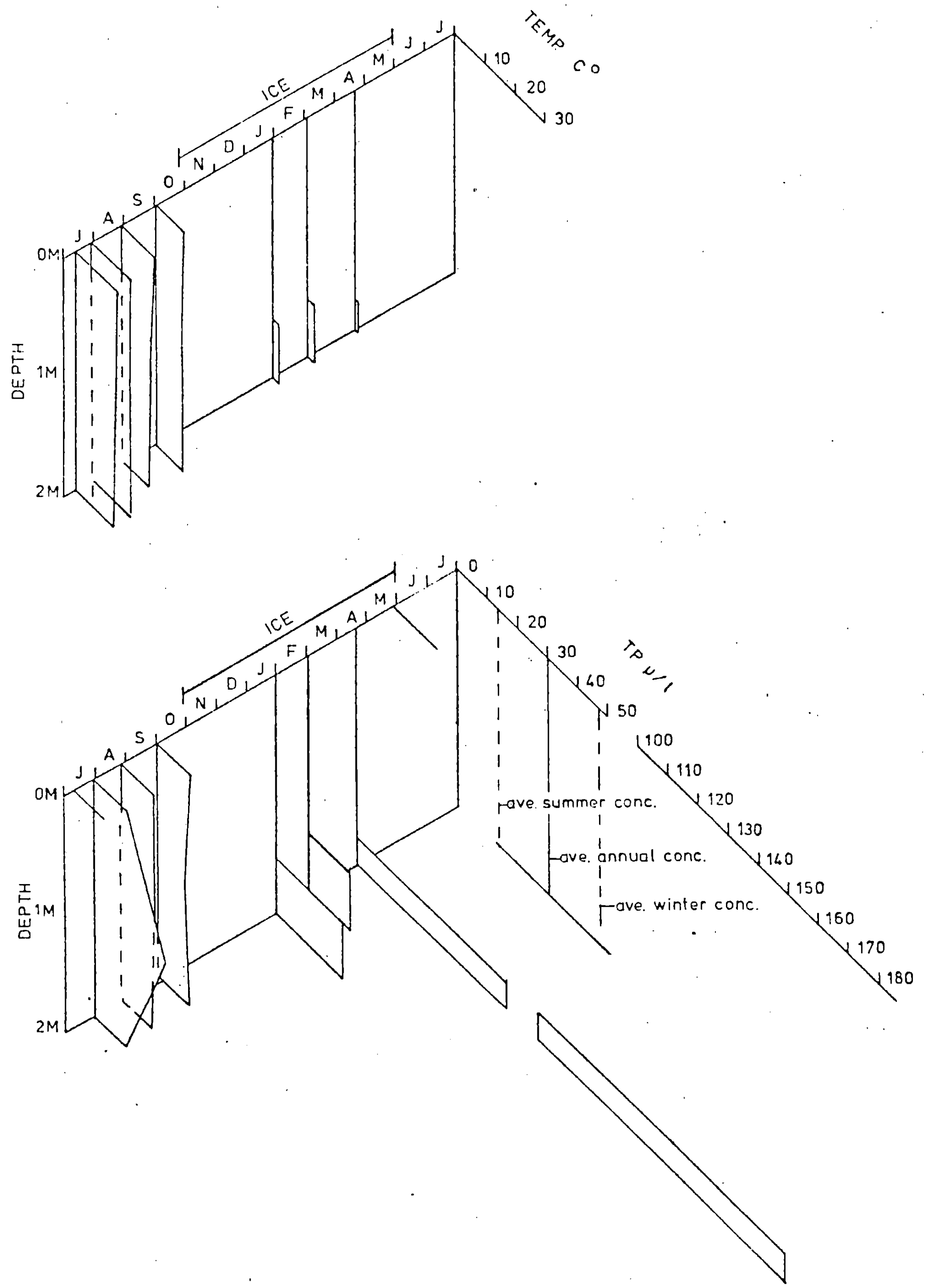


Figure 8. Data from Little Brooklyn Lake on temperature and total phosphorus, µg liter^{-1}. Note that the average phosphorus concentration calculated on an annual, summer and winter time scale is indicated on the TP axis ($[P_{LAn}]$, $[P_{LSum}]$, and $[P_{LWin}]$ respectively).

Unnamed Lake also had high phosphorus concentrations (23.2 ppb - 38.2 ppb) during the winter. This was opposed to conditions found during ice-free months when phosphorus concentrations ranged from 12.8 ppb to 16.2 ppb (Fig 9). Inlet and outlet phosphorus concentrations throughout the year ranged from 7.8 ppb to 15.2 ppb. Again because of high winter concentrations ($[P_{LWin}]$ = 30.0 ppb), $[P_{LAn}]$ and $[P_{LSum}]$ were not similar (18.7 and 11.4 ppb respectively; Table 2).

Towner Lake had about 11 ppb of phosphorus during summer months but a peak of 180 ppb occurred in April under the ice (Fig. 10). Inlet and outlet phosphorus concentrations were relatively low during the year (6.2 ppb - 36.2 ppb). As in the other two shallow lakes, $[P_{LAn}]$, $[P_{LSum}]$ and $[P_{LWin}]$ were quite different (30.0, 11.5 and 48.4 ppb respectively; Table 2).

Temperature profiles indicate that, with the exception of Big Brooklyn, the lakes do not stratify during the summer (Figs. 6 through 10).

Inlets and outlets showed peak volume flows during the run-off in early summer (Figs 11-15). Volume inflow was usually found to be slightly less than volume outflow indicating that water was flowing into the lakes from immeasurable sources (e.g., subterranean flow, surface run-off, small surface point sources). Annual discharges increased in each drainage system in a downstream direction. Big Brooklyn lake discharged 1,576,800 m^3 yr^{-1} (Table 1). In the Telephone drainage unnamed lake discharged 931,163 m^3 yr^{-1} and Towner 3,501,619 m^3 yr^{-1}. Because flushing rate is a function of both discharge and lake volume, ρ shows no trends within drainages. The lakes did, however, form 3 groups characterized by distinctly different ρ's; East Glacier and Big Brooklyn, $\rho \simeq 6$ yr^{-1}; Towner and Little Brooklyn $\rho \simeq 117$ yr^{-1}; Unnamed, $\rho \simeq 2300$ yr^{-1} (Table 1).

Phosphorus input and output followed the same trends as volume flow, peaks being observed during the runoff. Therefore, input and output values were largely functions of volume flow. Retention coefficients varied from .08 (Unnamed) to .32 Big Brooklyn (Table 1). All parameters pertinent to Dillon's phosphorus budget model are summarized in Table 1.

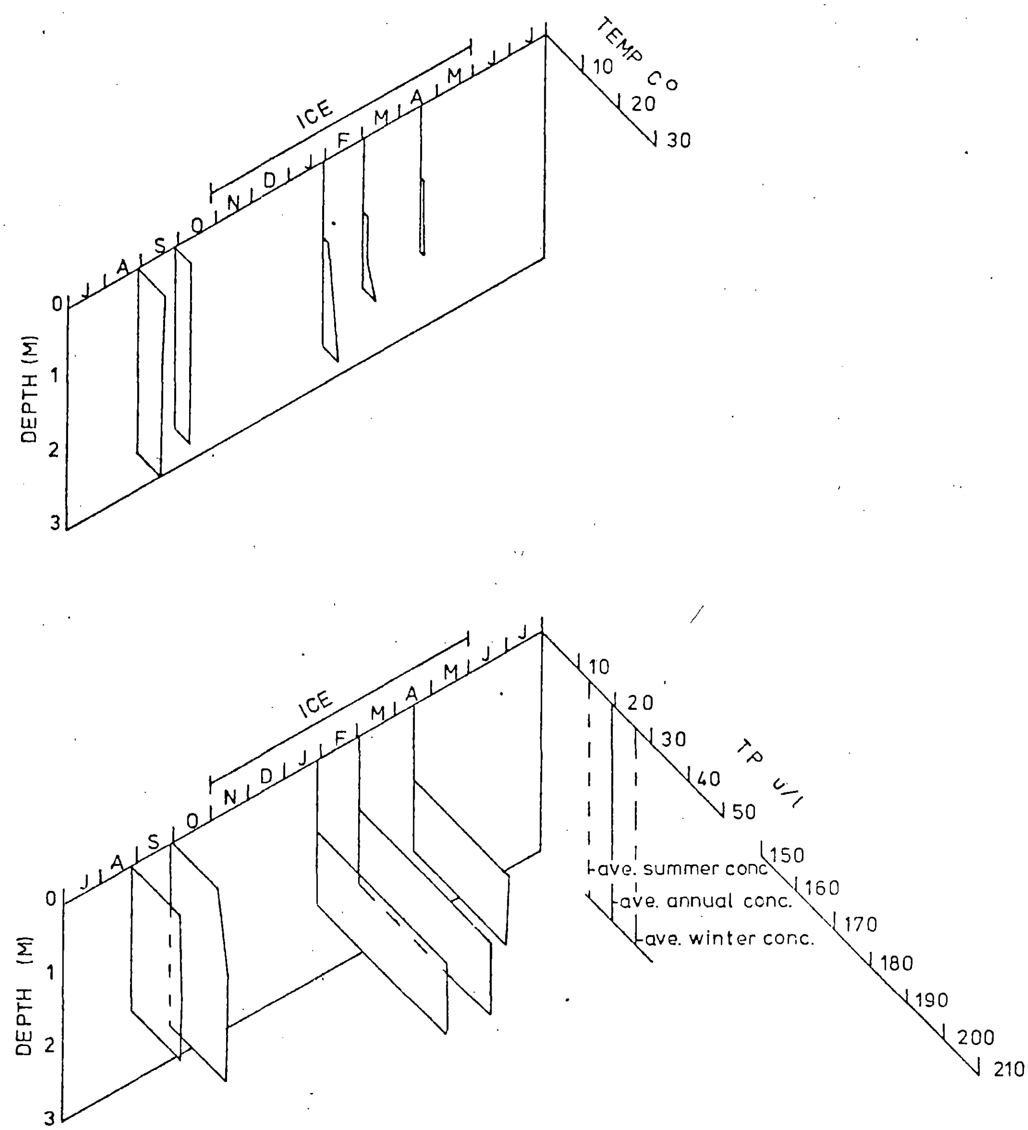
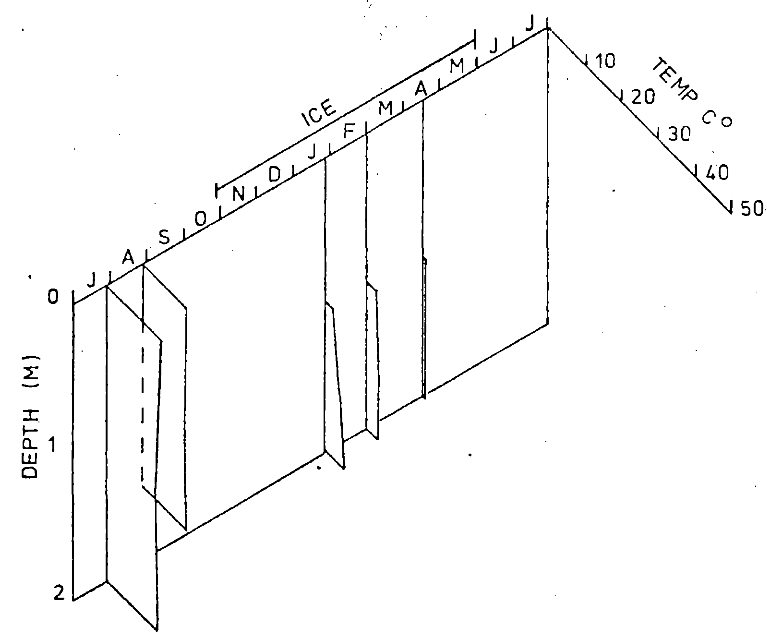


Figure 9. Data from Unnamed Lake on water temperature and total phosphorus, μg liter^{-1}. Note that the average phosphorus concentration calculated on an annual, summer and winter time scale is indicated on the TP axis ($[P_{LAn}]$, $[P_{LSum}]$, and $[P_{LWin}]$ respectively).



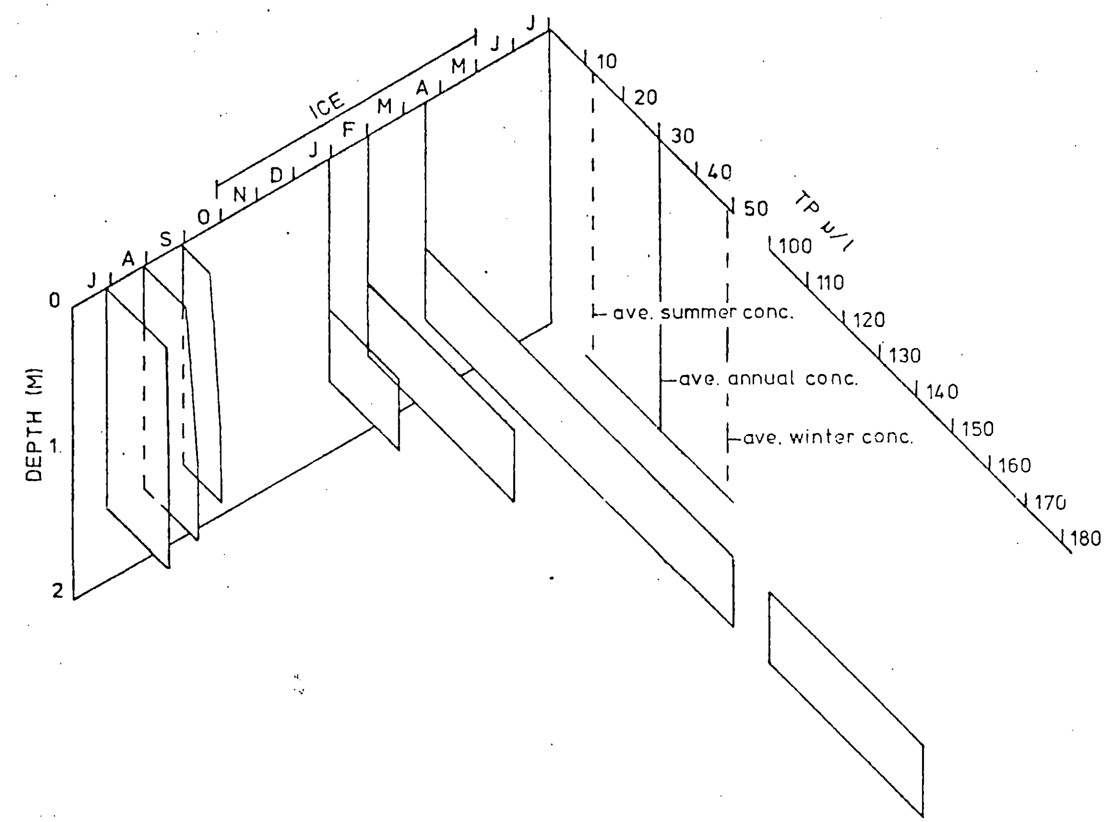


Figure 10. Data from Towner Lake on water temperature and total phosphorus, µg liter^{-1}. Note that the average phosphorus concentration calculated on an annual, summer and winter time scale is indicated on the TP axis ($[P_{LAn}]$, $[P_{LSum}]$, and $[P_{LWin}]$ respectively).

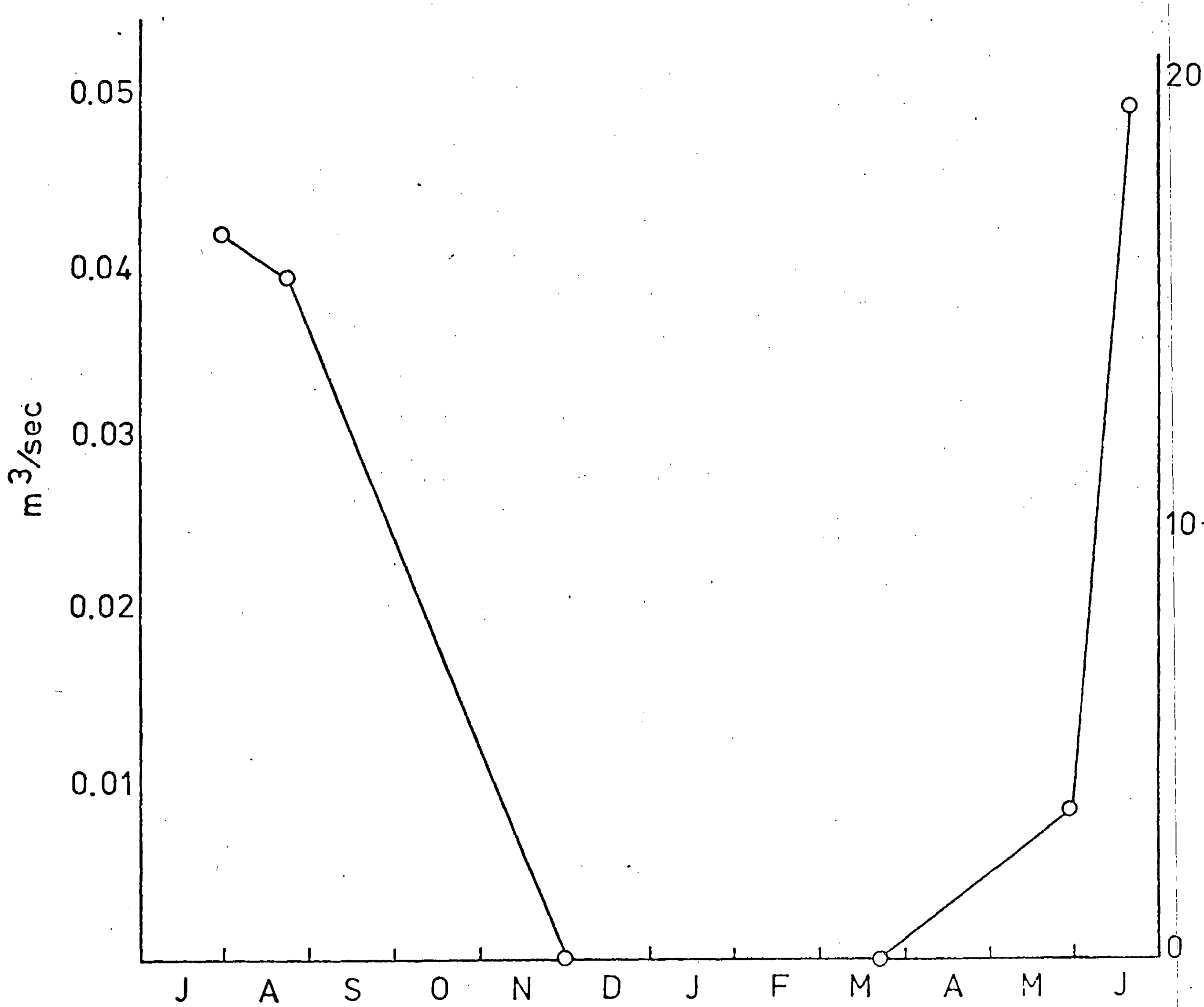


Figure 11. Data from East Glacier Lake on discharge of the outflow expressed as $m^3\ sec^{-1}$ and flushing rate, $\rho\ yr^{-1}$.

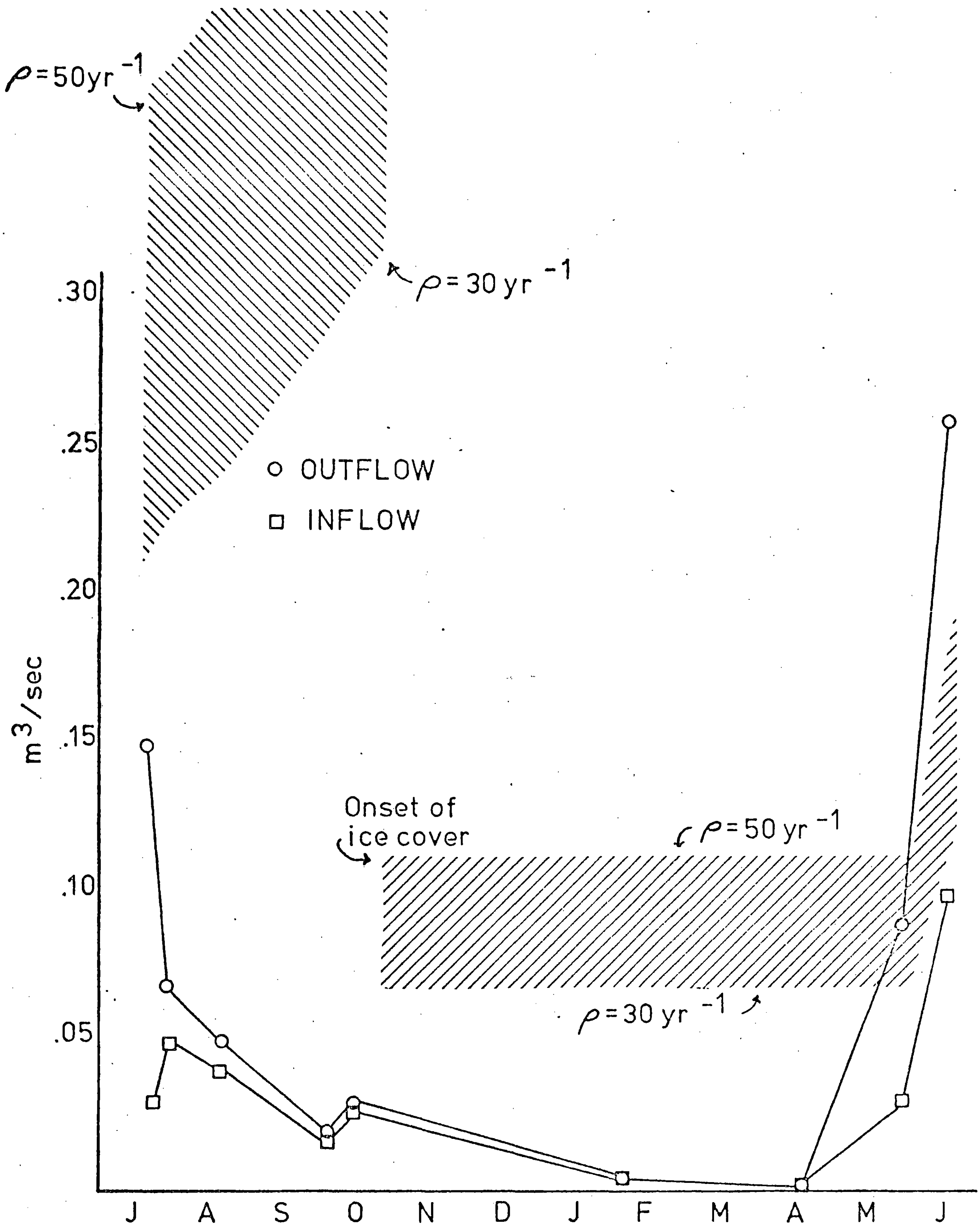


Figure 12. Data from Big Brooklyn Lake on the discharge of inflows and outflow, $m^3\ sec^{-1}$. Area above the hatching represents region C of Figure 23, area in the hatching represents region B, and area below the hatching represents region A.

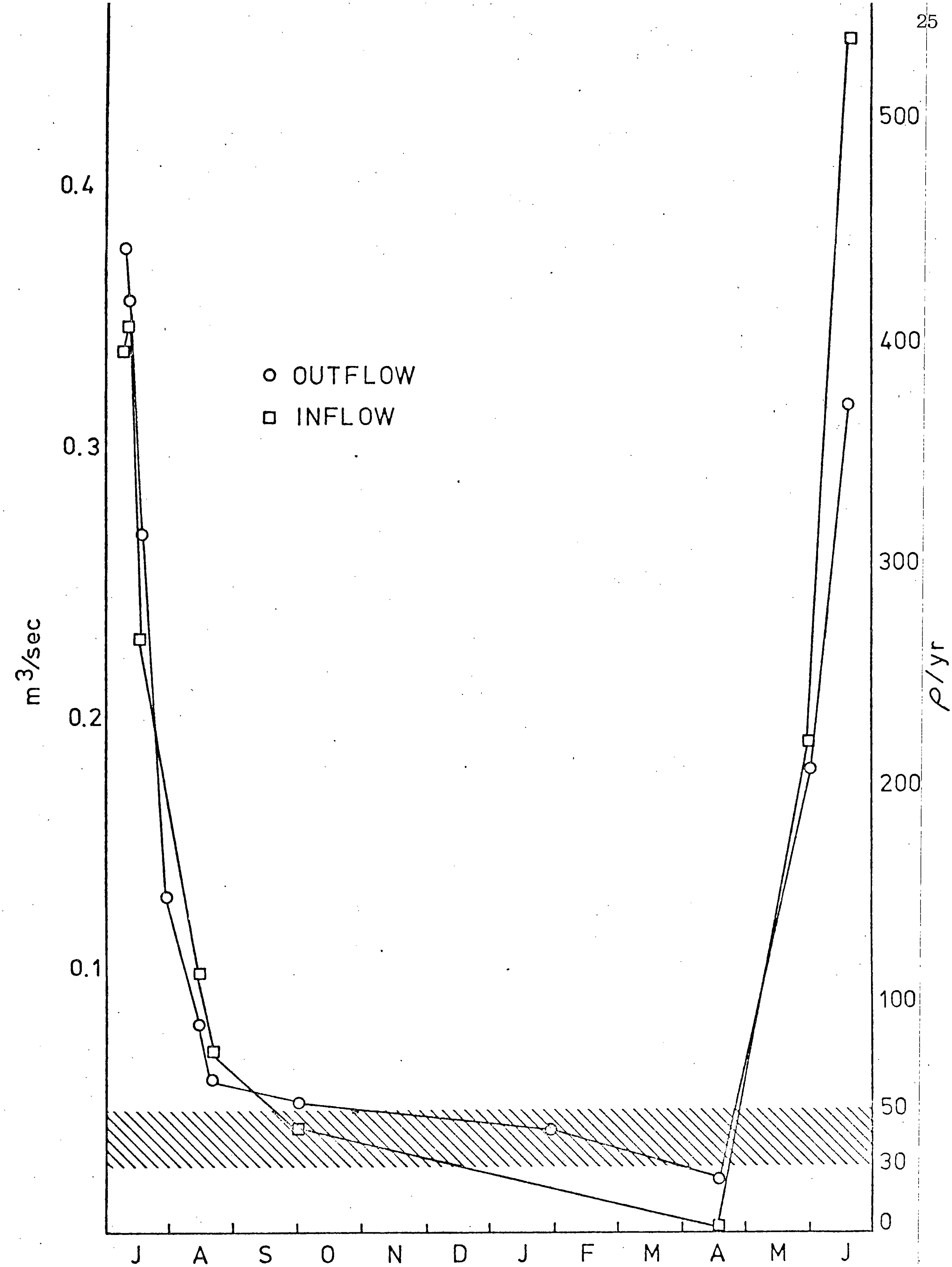


Figure 13. Data from Little Brooklyn Lake on the discharge of inflows and outflow expressed as $m^3\ sec^{-1}$ and flushing rate, $\rho\ yr^{-1}$. Area above the hatching represents region C of Figure 23, area in the hatching represents region B, and area below the hatching represents region A.

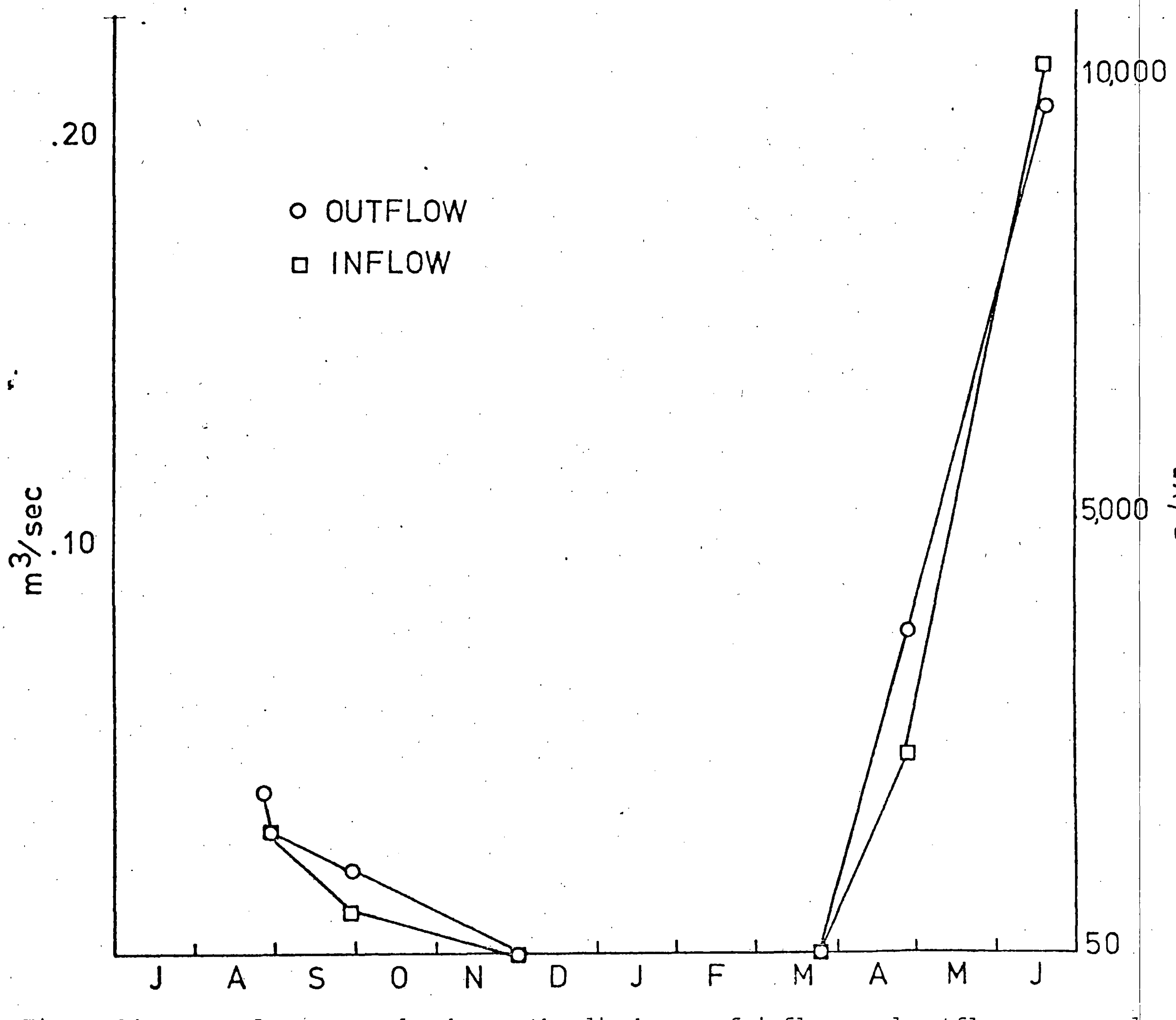


Figure 14. Data from Unnamed Lake on the discharge of inflows and outflow expressed as m^3 sec^{-1} and flushing rate, ρ yr^{-1}.

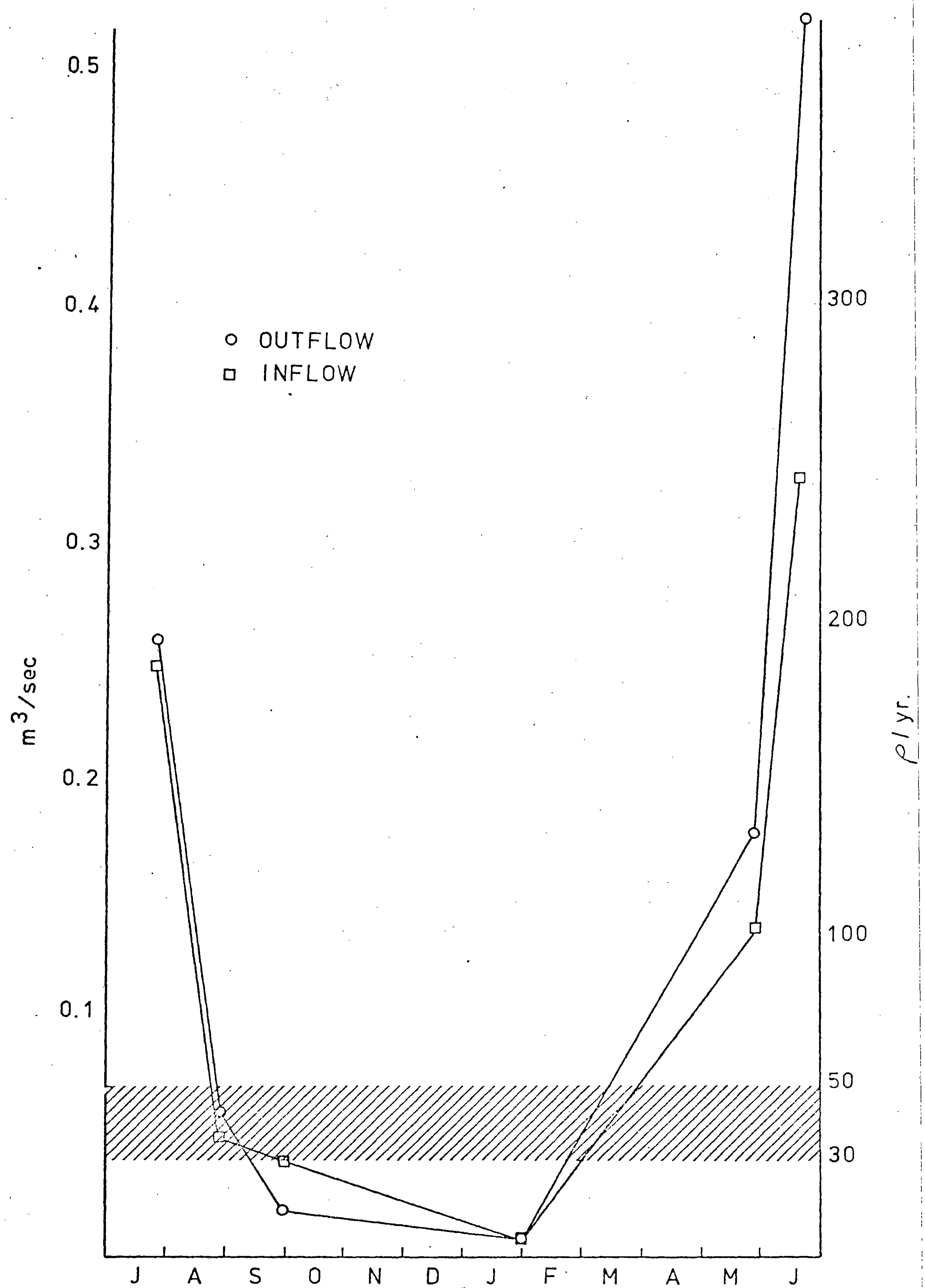


Figure 15. Data from Towner Lake on the discharge inflows and outflow expressed as $m^3 \ sec^{-1}$ and flushing rate, $\rho \ yr^{-1}$. Area above the hatching represents region C of Figure 23, area in the hatching represents region B, and area below the hatching represents region A.

Table 1. Morphometric, hydrologic and model (Eq. 2) parameters for the five study lakes; (—) indicates parameter could not be calculated.

	Symbol	East Glacier	Big Brooklyn	Little Brooklyn	Unnamed	Towner
Surface area (m^2)	SA	32,100	92,435	31,971	763	35,612
Volume (m^3)	V	76,025	299,308	32,479	648	44,944
Adjusted volume (m^3)	Vadj	62,836	264,924	24,734	409	29,473
Winter volume (m^3)	Vwin	49,648	230,541	16,990	170	14,002
Mean depth (m)	Z	2.4	3.2	.82	.85	1.2
Total discharge (m^3yr^{-1})	Q	—	1,576,800	2,862,091	931,163	3,501,619
Annual phosphorus input (g yr^{-1})	J	—	15,840	36,125	10,299	53,296
Annual phosphorus output (g yr^{-1})	O	—	10,740	27,778	9,460	45,412
Retention	R	—	.32	.23	0.08	0.15
Aerial loading (g $yr^{-1}m^{-2}$)	L	—	.17	1.13	13.5	1.49
Flushing rate (yr^{-1})	ρ	~5.0	6	116	2,278	119

Results of bioassays are presented in Figures 16-20. Algal growth in the Towner Lake bioassay of May was limited by nitrogen (Figs 16, 20 a, b, c). Incremental additions of nitrogen but not phosphorus caused significant increases in algal standing crop (significance at the 95% level was assigned using Student's T-test). The data indicate that where algal standing crop was increased by nutrient additions nitrogen was responsible. In the August bioassay of Towner Lake water the situation was reversed; phosphorus, not nitrogen, caused significant increases in standing crop during the bioassay (Figs 17, 20 a, b, c). Thus phosphorus was the limiting nutrient in these bioassays.

Bioassays of Big Brooklyn Lake produced quite different results from the Towner Lake bioassays. In both March and July algal standing crop increased only when combinations of phosphorus and nitrogen were added (Figs. 18-20 d, e, f). Thus both nitrogen and phosphorus were limiting nutrients in these bioassays.

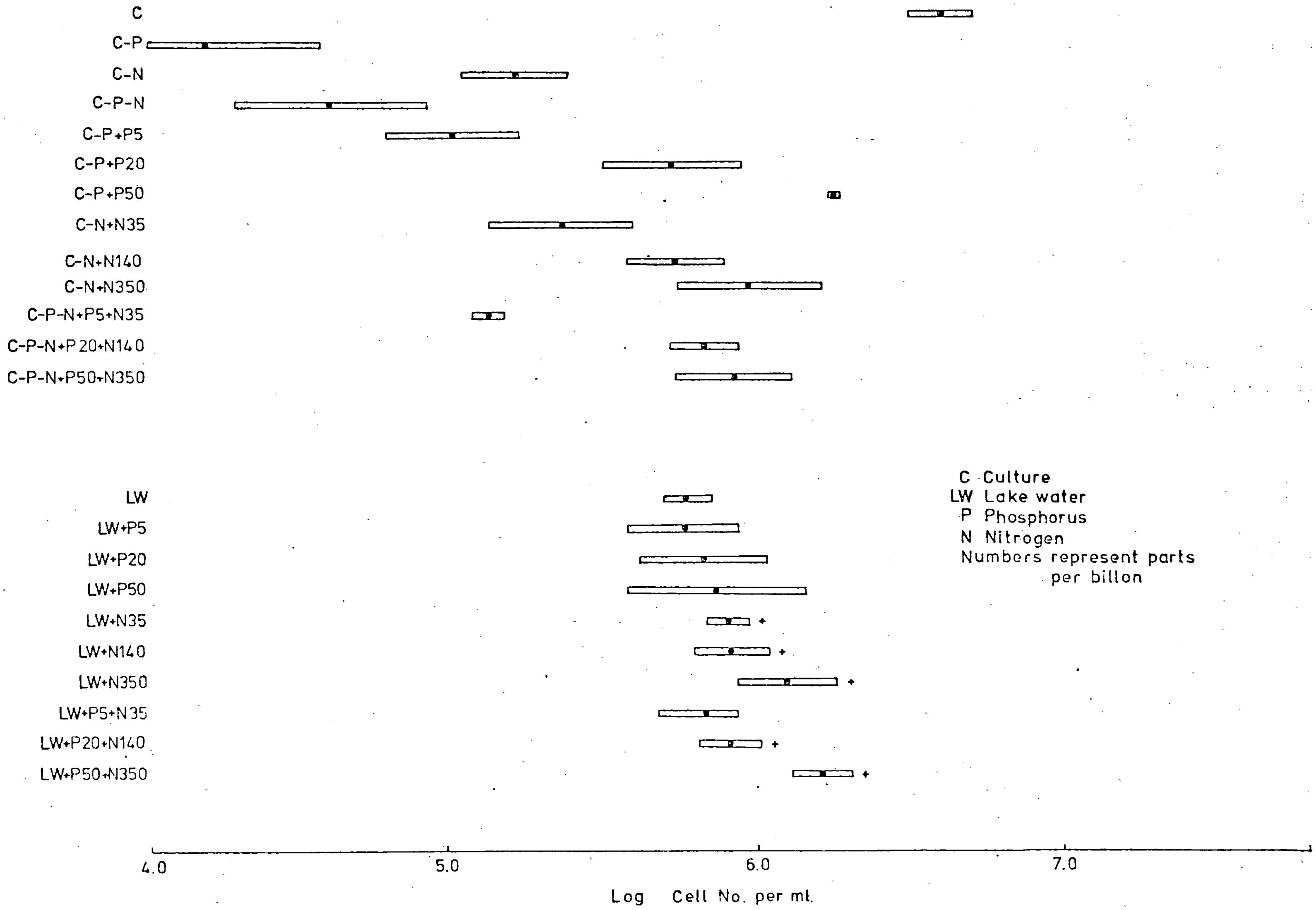


Figure 16. Data from all treatments of the May AAP-BT bioassay of water from Towner Lake. Data points are log (average number of cells ml^{-1}) and bars represent ± 95% confidence limits. The upper group of data represents treatments involving culture medium and the lower group represents lake water treatments. For the latter an "X" indicates the average cells ml^{-1} is significantly different from that in the treatment of lake water alone.

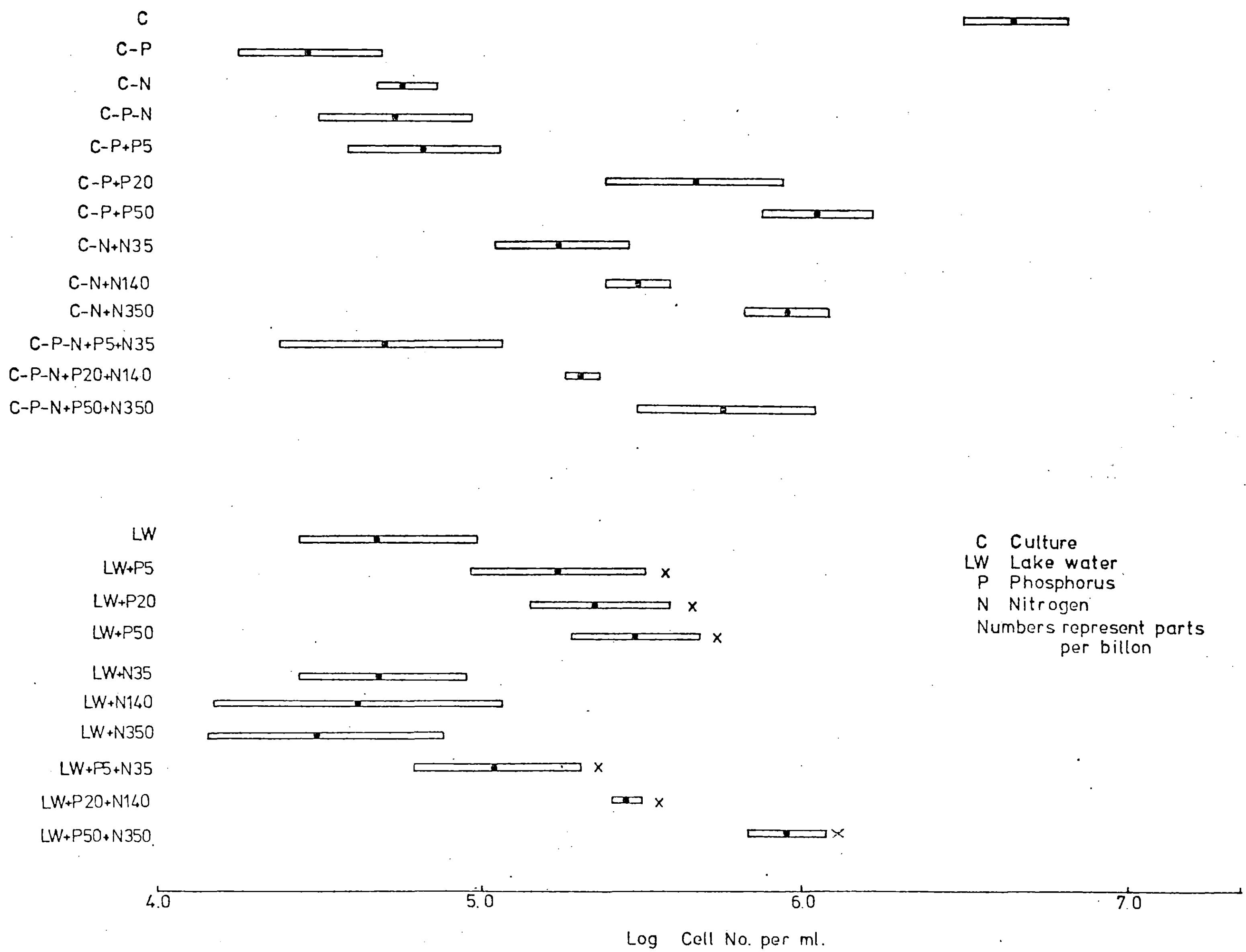


Figure 17. Data from all treatments of the August AAP-BT bioassay of water from Towner Lake. Data points are log (average number of cells ml^{-1}) and bars represent ± 95% confidence limits. The upper group of data represents treatments involving culture medium and the lower group represents lake water treatments. For the latter an "X" indicates the average cells ml^{-1} is significantly different from that in the treatment of lake water alone.

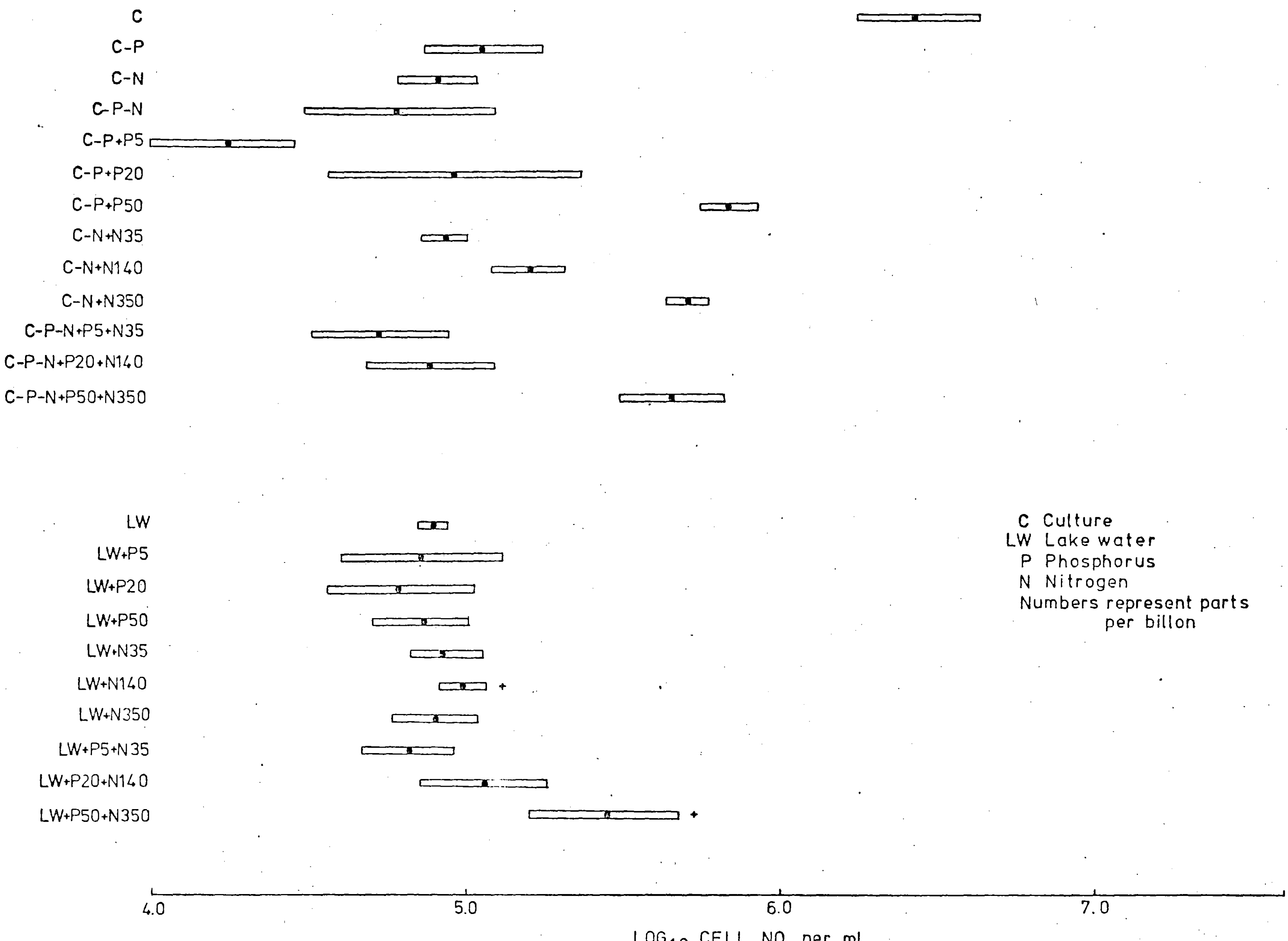


Figure 18. Data from all treatments of the March AAP-BT bioassay of water from Big Brooklyn Lake. Data points are log (average number of cells ml^{-1}) and bars represent ± 95% confidence limits. The upper group of data represents treatments involving culture medium and the lower group represents lake water treatments. For the latter an "X" indicates the average cells ml^{-1} is significantly different from that in the treatment of lake water alone.

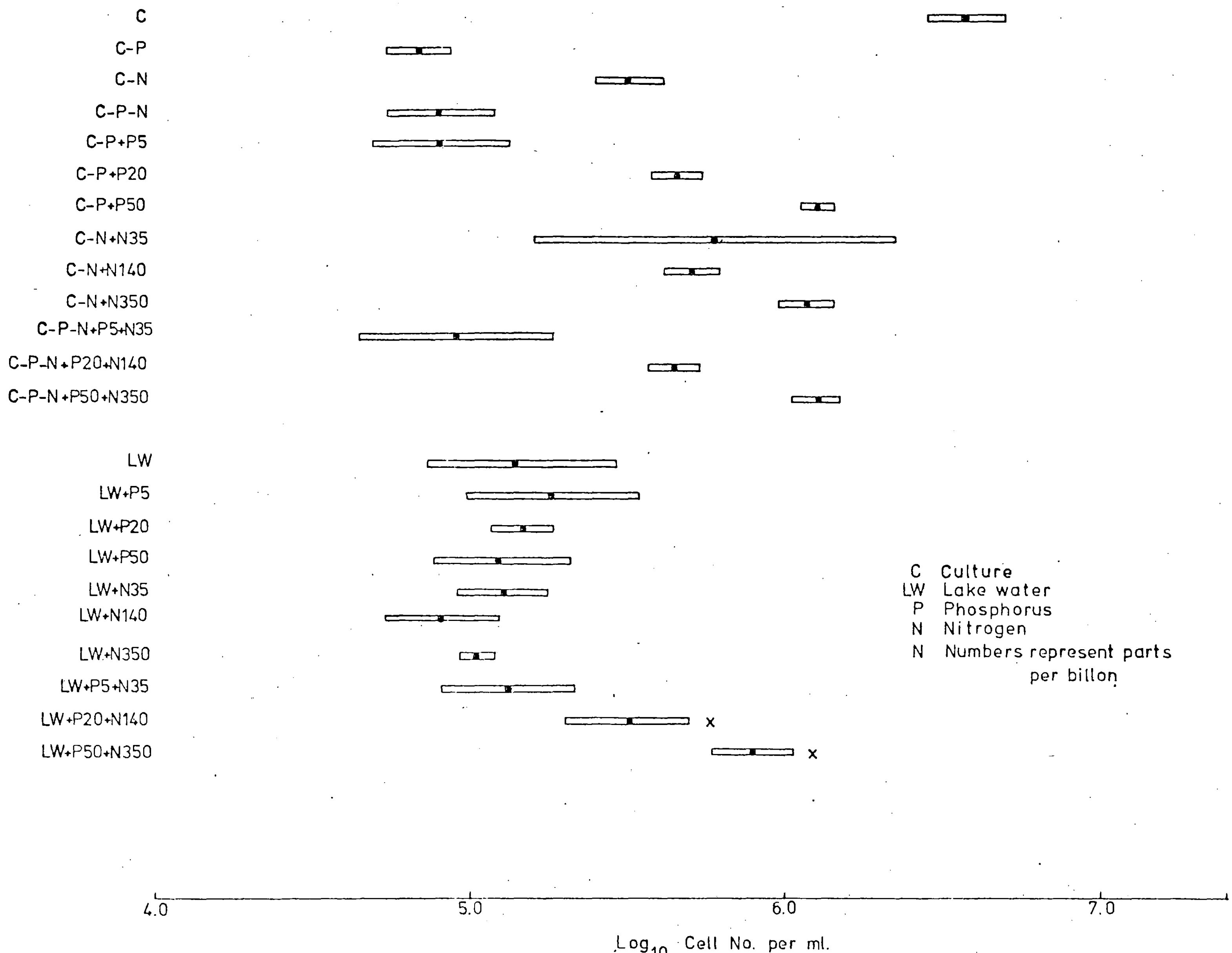


Figure 19. Data from all treatments of the July AAP-BT bioassay of water from Big Brooklyn Lake. Data points are log (average number of cells ml^{-1}) and bars represent ± 95% confidence limits. The upper group of data represents treatments involving culture medium and the lower group represents lake water treatments. For the latter an "X" indicates the average cells ml^{-1} is significantly different from that in the treatment of lake water alone.

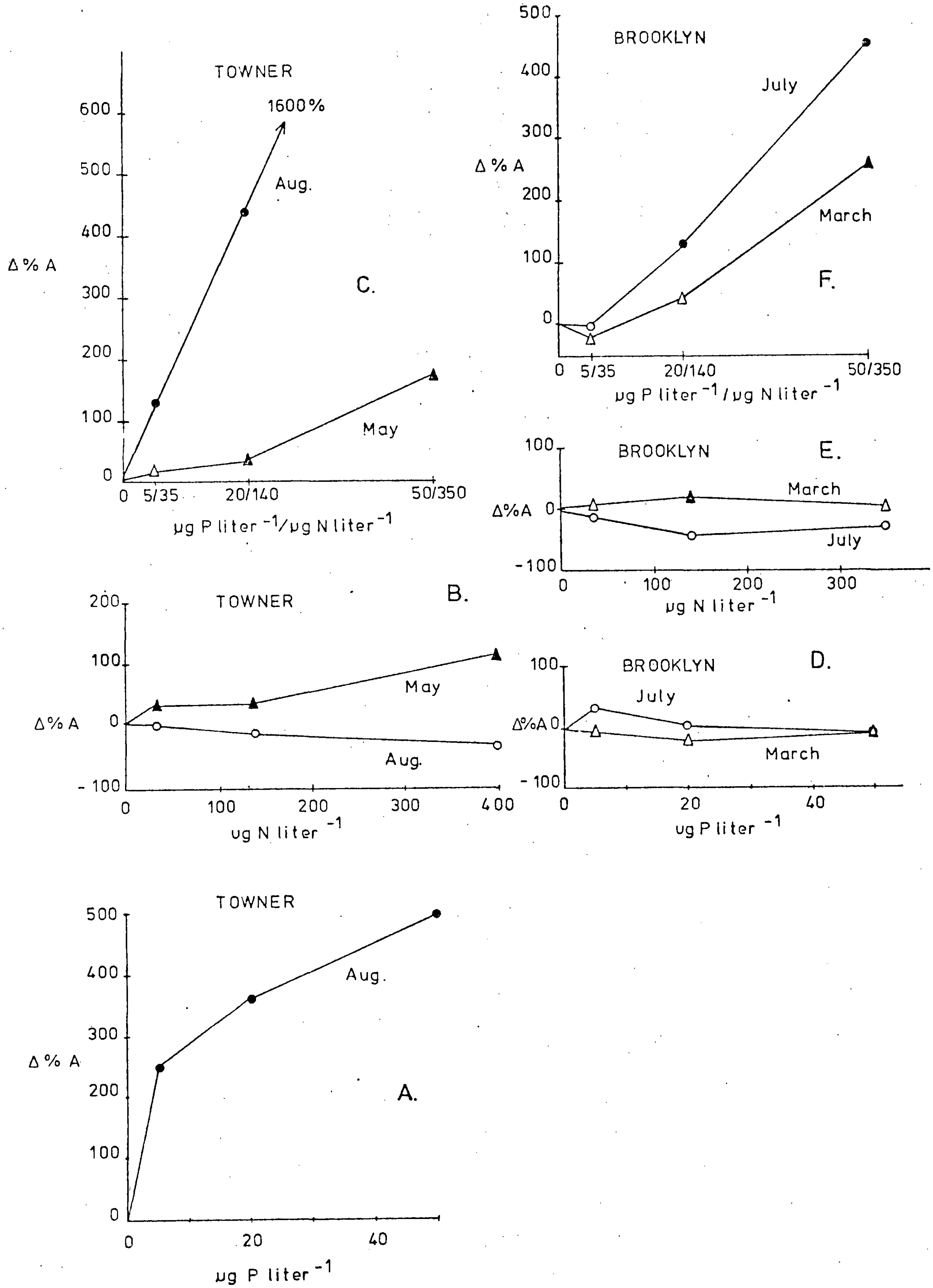


Figure 20. Percent increase in algal standing crop (Δ%A) which grew in autoclaved lake water as a function of the concentration of phosphorus, nitrogen, or phosphorus plus nitrogen added to the lake water; A, B and C Towner Lake; D. E and F Big Brooklyn Lake.

DISCUSSION

I. Field Problems

As anticipated, sampling the lakes during winter necessitated the use of skis for travel. The number of samples that were collected on any given trip was, therefore, limited because of weight considerations. Snow and ice cover during winter made finding inlets and outlets exceedingly difficult at times. Although we expected to dig through snow drifts to sample the streams, we forgot that locating them would be a problem under snow cover. We therefore neglected to mark our stream sampling sites and this was responsible for a lack of data at some locations.

Another problem which arose was that of taking flow measurements and phosphorus samples coincidentally. This was not always accomplished because of weather conditions, equipment failure or lack of time. Linear interpolation of flow was necessary where phosphorus but not flow data was available on a given date.

The hazards of thin ice precluded sample collection on the lakes in late fall and during the spring melt. The absence of phosphorus data at these times resulted in questionable interpolation from one season to the next. However, due to obvious trends in the data it was felt that error was minimized.

II. Measured and Predicted Phosphorus Concentrations

Almost all other investigations which tested Eq. 2 studied lakes similar to Big Brooklyn; mean depths were several to many meters, and flushing rates were not extremely large. For example, 11 of the 13 Ontario lakes studied by Dillon and Rigler (1974) had mean depths greater than 3m and flushing rates of less than 17 yr^{-1}. Certainly all these lakes depart to some degree from the assumptions of

Eq. 2 (e.g., most or all of these lakes stratify thermally during the summer; this violates the assumption of a uniformly mixed lake). However, Eq. 2 still reasonably predicted [P] at spring turnover, an estimate of [P_{LAn}]. Thus although processes in previously studied lakes deviate from the assumptions of Eq. 2, they approximate the assumptions closely enough so that predictions are often remarkably accurate.

In none of our study lakes did Eq. 2 accurately predict [P_{LAn}] (Table 2). Only in Big Brooklyn Lake did [P_{Pred}] even approximate the actually measured [P_{LAn}]. But surface phosphorus concentrations later in the summer were fairly close to the predicted value. We suggest that this occurred because only then did the epilimnion of the lake have a flushing rate which was 30 yr^{-1} or less. Our reasoning is explained in detail later (Section IV-A, page 43). Briefly, the hydrologic characteristics of the lake are such that early in summer the assumptions of Eq. 2 are not fulfilled; late in summer they are approximated as in the lakes studied by Dillon and Rigler.

Unlike Big Brooklyn Lake, in the shallow lakes we studied, Little Brooklyn, Unnamed and Towner, the measured [P_{LAn}] exceeded the predicted value by 200% or more (Table 2). Anoxic conditions occurred for most of the ice-covered period in Unnamed and Towner Lakes, and for a much lesser time in Little Brooklyn Lake. As a result phosphorus concentrations were high in Unnamed and Towner Lakes for most of the winter (Figs. 9-10). The large [P_{LWin}] values account for some of the difference between [P_{Pred}] and [P_{LAn}] in the shallow lakes, because the model does not consider the conditions producing the increased concentrations in winter.

But winter conditions do not account for all the difference between the predicted and measured [P_{LAn}] in these shallow lakes. Note that the average phosphorus concentrations during the ice-free period, [P_{LSum}], were still 50-80% more than predicted (Figs. 8-10; Table 2). [P_{LSum}] is, however, approximately equal to the

Table 2. Phosphorus concentrations predicted from Eq. 2., $[P_{Pred}]$, and actually measured, $[P_{LAn}]$, $[P_{LSum}]$, $[P_{LWin}]$, $[P_{If}]$, in the study lakes. Phosphorus concentration is expressed as μg P liter^{-1}. Percentage values for lake concentrations were calculated as $[(100[P_L]/[P_{Pred}])-100]$.

Lake	Stream $[P_{If}]$	Lake $[P_{LAn}]$	Lake $[P_{LSum}]$	Lake $[P_{LWin}]$	Equation 2 $[P_{Pred}]$
Unnamed	11	18.7/192%	11.4/78%	30.0/369%	6.4
Towner	15	30.0/241%	11.5/31%	48.4/450%	8.8
Big Brooklyn	10	10.1/68%	9.5/58%	10.6/77%	6.1
Little Brooklyn	13	30.5/231%	13.4/46%	47.6/417%	9.2
E. Glacier	--	10.1	8.5	11.8	--

average concentration of phosphorus in the inflow, $[P_{If}]$ (Table 2). From inspection of Eq. 2 it can be seen that if retention of phosphorus in the lake, R, approaches zero the $[P_{LAn}]$ will approach $[P_{If}]$. This is represented graphically below (Fig. 21) where change in the slope of the curve represents $R \rightarrow 0$. R, and the slope of the curve should change as a function of flushing rate, ρ, because as ρ becomes large there is less and less chance for phosphorus to be retained in the lake. In essence, as ρ becomes very large the lake becomes a stream. The physical effect of flushing dominates the processes usually occurring in lakes, and that Eq. 2 assumes to occur.

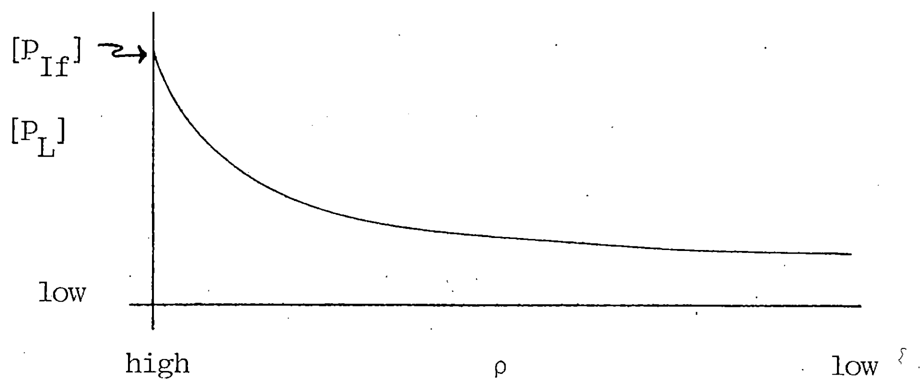


Figure 21

Dillon and Rigler (1974) concluded from a study of 17 lakes that Eq. 2 reasonably predicted $[P_{LAn}]$ ($r \simeq 0.92$) when data from two shallow ($\bar{z}$ of 0.73 m and 0.85 m) lakes were excluded from their analysis. The $[P_{LAn}]$ measured in one of the latter lakes was about twice that predicted. Garn and Parrott (1977) suggest that this is reasonable because the effects of wind and waves can cause greater disturbance of sediments than in deeper lakes, and because such an effect is not accounted for by the model. We concur with this conclusion. But we also suggest that when ρ is very large it will also affect the expected values of $[P_{LAn}]$ and $[P_{LSum}]$.

In summary, Eq. 2 approximately predicts $[P_{LAn}]$ and $[P_{LSum}]$ for Big Brooklyn Lake. This was the lake most like the large number of other lakes to which Eq. 2

has been successfully applied; it is deeper and has a relatively small annual flushing rate. These are attributes which insure processes in the lake reasonably approximate the assumptions underlying the model. However, the flushing regime is such that Eq. 2 is not expected to predict phosphorus concentrations accurately until late summer (see Discussion Sections IV-A, page 45). In the shallow lakes, Little Brooklyn, Unnamed and Towner, Eq. 2 drastically underestimated both $[P_{LAn}]$ and $[P_{LSum}]$. Their shallowness and rapid flushing cause processes to dominate which are not accounted for by the model, and hence predictions are inaccurate.

III. Bioassays

Data from the bioassays of water from Towner Lake indicate that nitrogen but not phosphorus was limiting under the ice (Figs. 16, a,b; 20 a,b,c). This is not surprising because phosphorus concentrations were very high owing to anoxia (Fig. 10), and adding nitrogen in the bioassays allowed this excess phosphorus to be utilized by Selenastrum. Note that treatments of nitrogen plus phosphorus did not produce $\Delta\%A$ significantly different from treatments of nitrogen alone (Fig. 20 b,c). The significant difference between the phosphorus and phosphorus plus nitrogen curves for August occurred at the greatest nutrient addition (Fig. 20 a,c). The addition of 50 μg P l^{-1} alone produced a $\Delta\%A$ of 500%, but when nitrogen was also added the curve increased linearly to a $\Delta\%A$ of 1600%. Thus the added nitrogen allowed complete utilization of the phosphorus.

Unlike Towner Lake, phytoplankton in Big Brooklyn Lake were limited by both phosphorus and nitrogen on a short-term basis (see below). Neither element when added alone increased $\Delta\%A$ (Fig. 20 e,d). However, addition of phosphorus plus nitrogen resulted in larger $\Delta\%A$ during both winter and summer (Fig. 20 f).

Before using the bioassay data to predict what will occur in the lakes we must first distinguish between the short-term (days) and long-term (months, years) effects of nutrient addition to lakes (Parker 1977). We are interested in

long-term effects. Next we must decide what bioassay treatments to employ when predicting the long-term effects. To do this we start by assuming there is excess phosphorus in a lake compared to nitrogen. When nitrogen becomes depleted it will limit algal standing crop on a short time scale. However phosphorus is still present in concentrations allowing algal growth if more nitrogen were available. Nitrogen fixation is a process which can provide this additional nitrogen and which thus allows utilization of the excess phosphorus until the latter limits algal standing crop. Similarly, assume a lake with excess phosphorus compared to carbon dioxide. When carbon dioxide is depleted by photosynthesis, more diffuses into the lake from the atmosphere and eventually phosphorus limitation occurs (e.g. Schindler 1975). Thus on a long-term basis carbon should not limit phytoplankton standing crop, and neither should nitrogen if nitrogen fixers occur in the lake. But phosphorus in a lake cannot be supplemented from the atmosphere as are carbon and nitrogen, and hence it limits algal standing crop when depleted. Using this reasoning Parker (1977) argued that if nitrogen fixing algae occur in a lake the appropriate bioassay treatment to predict the long-term $\Delta\%A$ resulting from altered phosphorus loading is the phosphorus plus nitrogen treatment (i.e., Fig. 20 c,f). This is because the bioassay algae cannot fix nitrogen; the nitrogen added with phosphorus to the bioassay flasks is functionally equivalent to nitrogen fixation in the lake.

Because species capable of fixing nitrogen occur in Big Brooklyn Lake, and many other lakes in the Snowy Range (Hepworth, 1959; Condit, 1974; B. R. Shero, personal communication), we use the bioassay treatments of phosphorus plus nitrogen to predict $\Delta\%A$. However, for management decisions we want to predict $\Delta\%A$ as a result of alterations in the drainage basin such as roads, campgrounds, or second home development. Various authors have compiled data on the expected increase in phosphorus loading to a lake as a consequence of alterations in the watershed (e.g. Lerman, 1974; Dillon & Kirchner, 1975; Kirchner, 1975; Garn and Parrott, 1977).

Parker (1977) suggests that is is most useful to use such data to compute the percent increase in the areal phosphorus loading of the lake, $\Delta\%L$, as

$$\Delta\%L = \left(\frac{\text{New } L}{\text{Present } L} - 1\right) x100 \qquad \text{Eq. 4}$$

Next he also expresses $[P_{LAn}]$ of Eq. 2 as a percent change in a lake's present phosphorus concentrations, $\Delta\%P$.

$$\Delta\%P = \left(\frac{\text{New } [P_{LAn}]}{\text{Present } [P_{LAn}]} - 1\right) x100 \qquad \text{Eq. 5}$$

Then using Eqs. 4 and 5 he modifies Eq. 2 to calculate the percent change in $[P_{LAn}]$ as a function (f) of the percent change in phosphorus loading.

$$\Delta\%P = f\ (\Delta\%L) \qquad \text{Eq. 6}$$

Next he converts the abcissa of Fig 20 c,f from phosphorus concentration to $\Delta\%P$.

$$\Delta\%A = g\ (\Delta\%P) \qquad \text{Eq. 7}$$

Substituting Eq. 6 in Eq. 7 we obtain the desired result, an equation predicting $\Delta\%A$ as a function of any increase in $\Delta\%L$.

$$\Delta\%A = g\ [f(\Delta\%L)] \qquad \text{Eq. 8a}$$

Recall that the $\Delta\%L$ expected from various types of development can be predicted from data in the literature.

The numerical version of Eq. 8a for Big Brooklyn Lake is obtained using data from the July bioassay treatment of nitrogen plus phosphorus.

$$\Delta\%A = 0.5\Delta\%L \qquad \text{Eq. 8b}$$

Figure 22a graphically represents Eq. 8b. The abscissa is scaled in three ways: as $\Delta\%L$; as $\Delta\%J$; and as ΔL, or $L_{new} - L_{present}$. For Towner Lake the August bioassay treatment of nitrogen plus phosphorus is used to obtain

$$\Delta\%A = 2.7\Delta L \qquad \text{Eq. 8c}$$

This equation is represented by Figure 22b.

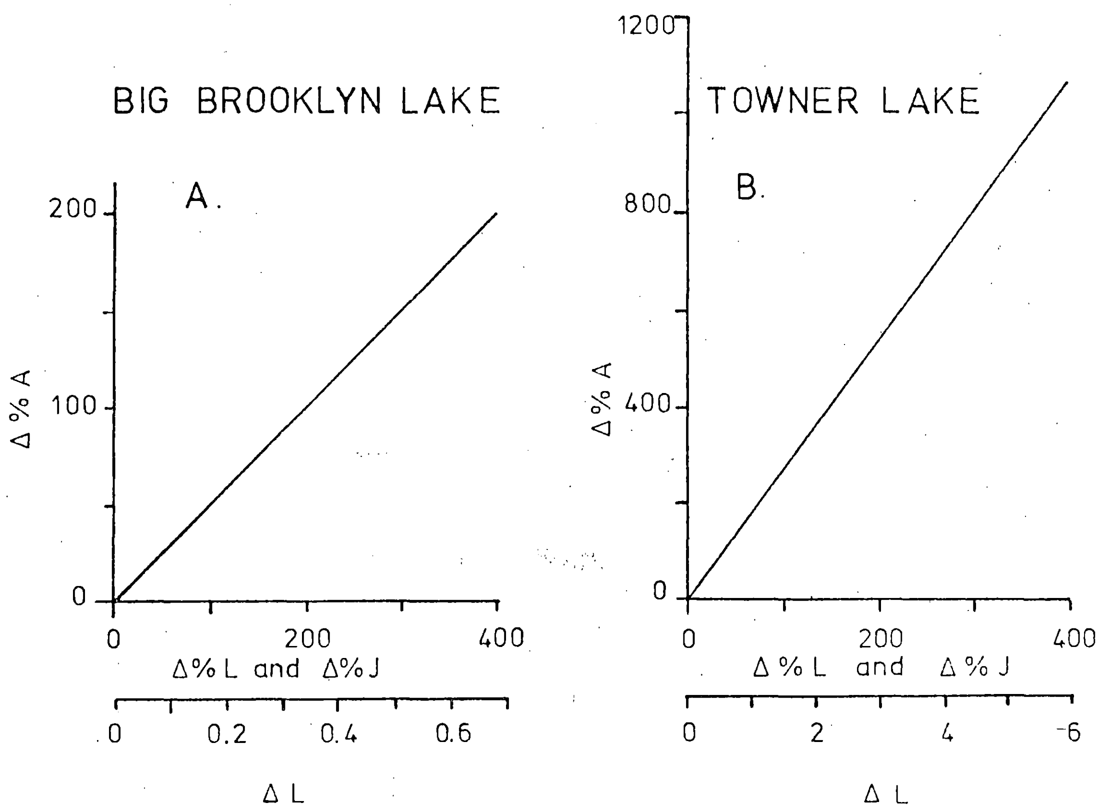


Figure 22. The percent by which phytoplankton standing crop will increase (Δ%A) as a function of an increased annual phosphorus loading Eq. 8 of text). Phosphorus loading is scaled as Δ%L, Δ%J (percent change in the annual areal loading, and total annual loading), and ΔL (an increase above present annual areal loading, g m^{-2} yr^{-1}); A, data from Big Brooklyn Lake; B, data from Towner Lake. See text for complete explanation.

IV. Predicting the Effects of Increased Phosphorus Loadings

A. Introduction

When lakes do not have very large flushing rates, ρ, Eq. 8 (or Fig. 22) is used as follows. Estimates of the increased L are made which should result from a proposed development. This value is converted to $\Delta\%L$ and $\Delta\%A$ is calculated or read from the graph. However, this procedure will produce drastic overestimates of $\Delta\%A$ if ρ is very large. This occurs because when ρ is large phytoplankton losses from washout increase as ρ increases. And, when losses of phytoplankton standing crop by flushing exceed reproductive gains algal standing crop will actually decrease. Thus if losses owing to ρ equal or exceed the reproductive rate of phytoplankton, then increases in L will will have no effect on $\Delta\%A$.

This argument is illustrated graphically by Figure 23. When a lake is in region A it should respond to phosphorus loadings as predicted by Eqs. 2 and 6 (i.e. $[P_{LAn}] = [L(1-R)]/(\overline{Z}\rho)$ and $\Delta\%P = f(\Delta\%L)$), $\Delta\%A$ should be predicted by $g(\Delta\%P)$ (Eq. 7), and hence $\Delta\%A$ can be calculated by $g[f(\Delta\%L)]$ (Eq. 8). In region C $\Delta\%A$ should not increase with increases in L; the physical effect of ρ makes $\Delta\%A$ independent of L or $[P_{An}]$. Note also that in region C the maximum $[P_{LAn}]$ equals $[P_{IFAn}]$.

Thus far we have discussed a lake's response to phosphorus loadings in terms of the percent change which will occur in phytoplankton standing crop or $\Delta\%A$. Other workers have used different indicies. For example Vollenweider (1968) suggested that 10 mg Pl^{-1} at spring overturn approximated the boundary between oligo- and mesotrophic lakes. He also suggested 20 μg Pl^{-1} demarcates meso-and eutrophic lakes. Carlson (1977) developed a Trophic State Index, TSI, or a single number designating the state of a lake. TSI can be calculated from data on secchi desk readings, surface concentrations of total phosphorus, or surface

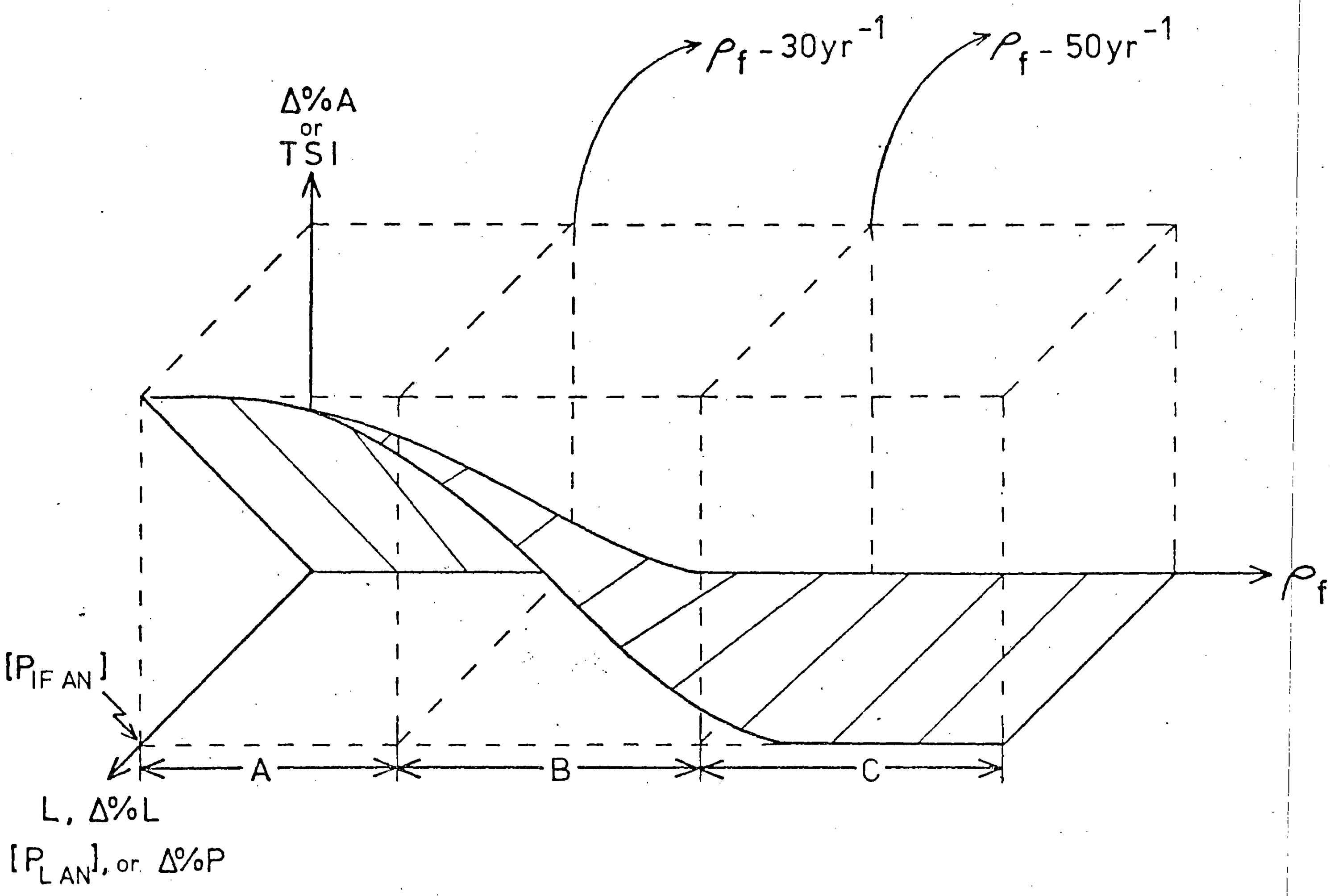


Figure 23. The percent by which phytoplankton standing crop (Δ%A) or Trophic State Index (TSI) will increase as a function of increased phosphorus loading and flushing rate, ρ. Increased phosphorus loading is measured by areal loading (L, or Δ%L) or the phosphorus concentration in lake water ([P_{LAn}] or Δ%P). See text for complete explanation.

concentrations of chlorophyll. For example 2 mg chl a m^{-3} results in a TSI of 37 and 4 mg chl a m^{-3} a TSI of 47; these concentrations approximate the boundaries between oligo-/mesotrophic and meso-/eutrophic as suggested by Vollenweider. Thus if we had data on the present mg chl a m^{-3} of our study lakes the ordinate of Figure 22 could be scaled as TSI. The ordinate of Figure 23 is scaled as both $\Delta\%A$ and TSI.

Before we can utilize Figure 23 (or Fig. 22 and Eq. 8) to aid in making management decisions we must first determine the values of ρ which delimit regions A, B and C. Parker (1975) studied Libby Lake, a lake which is morphometrically and hydrologically similar to Big Brooklyn Lake. Both lakes are deep enough to stratify thermally in summer and are located only 1.4 km apart. Parker found that when ρ was about 50 yr^{-1} or greater algal standing crop decreased in the flushing layer (i.e. the epilimnion after ice-off). Note that ρ of the flushing layer will be directly proportional to discharge but inversely proportional to the volume of the layer. Thus given a constant discharge, ρ of the flushing layer will decrease as the depth of the epilimnion increases through the summer. The flushing rate of the flushing layer will hereafter be designated us ρ_f to distinguish it from ρ, (annual discharge)/(total lake volume). However, note that if a lake does not stratify then $\rho = \rho_f$.

Based on the above we suggest that $\rho_f \approx 50$ yr^{-1} or greater characterizes region C of Figure 23. If a ρ_f of 50 yr^{-1} just offsets algal reproduction there will be no change in standing crop. This represents a net algal growth rate of 0.14 d^{-1} of a doubling time of 5d. Based on less substantial data we suggest that the lower limit of ρ_f in region C is about 30 yr^{-1}. This ρ_f is equivalent to a net algal growth rate of about 0.08 d^{-1} and a doubling time of about 9d. Having characterized the ρ_f values of regions A, B and C we now consider data from the study lakes, and determine whether $\Delta\%A$ should increase as a result of increases in $\Delta\%L$.

B. Effects on the Five Study Lakes

1. East Glacier Lake

East Glacier Lake stratifies thermally little if any during summer and so $\rho = \rho_f$. ρ is always less than 30 yr^{-1} (Fig. 11) and the lake is thus in region A of Figure 23. It will respond to increased phosphorus loading by increasing $\Delta\%A$ and TSI. Because it is in the same drainage as Big Brooklyn we assume Eq. 8b or Figure 22c predicts $\Delta\%A$.

2. Big Brooklyn Lake

Unlike East Glacier Lake Big Brooklyn stratifies thermally during summer. Therefore $\rho_f = \rho$, and ρ_f will vary as both the volume flow of runoff and the depth of the flushing layer (epilimnion after ice-off) change through time. The lower limit of the hatched area of Figure 12 represents $\rho_f = 30$ yr^{-1}, and the upper limit represents $\rho_f = 50$ yr^{-1}. In those months when the curve representing outflow is below the hatched area the lake's flushing layer is in region A of Figure 23. Then the outflow curve is in the hatched area the flushing layer is in region B, and when outflow is above the curve the flushing layer is in region C. Thus when the lake is ice covered $\Delta\%A$ (and TSI) should increase owing to increased phosphorus loading. But in late April or May, shortly after snowmelt begins, the flushing layer of the lake passes quickly from region A to region C. And for the first part of the growing season, mid-May to early July, increased phosphorus loading should not increase $\Delta\%A$ or TSI in the flushing layer. In mid-July the lake's flushing layer passes from region C to region A, remaining there until the onset of snowmelt the next year. Thus for the last 1.5 to 2 months of the growing season $\Delta\%A$ and TSI will increase if phosphorus is added to the lake, and $\Delta\%A$ should be predicted by Eq. 8b or Figure 22c.

In addition to the above there is another complication to consider when predicting the effects of increased phsophorus input to Big Brooklyn Lake. Parker (1975) found that in Libby Lake sufficient light always penetrated below

the flushing layer to permit photosynthesis. As a result, during the first part of the growing season tremendous phytoplankton standing crops accumulated in the hypoliminion (ca. 30 mg chlorophyll a m^{-3}) compared to those in the flushing eplimnion (ca. 2 mg chl a m^{-3}). Without doubt this also presently occurs in Big Brooklyn Lake.

Now consider what will occur to phytoplankton standing crop if the Δ%L of Big Brooklyn Lake increases. We assume that the new phosphorus does not reach the hypolimnion; if it does it will exacerbate the situation described below. Until the flushing layer moves from region C to A in mid-July the lake will be as at present, with a large standing crop in the hypolimnion under an epilimnion with a small attenuation coefficient. But by late July or early August algal standing crop in the epilimnion will increase and the attenuation coefficient will increase. The larger attenuation coefficient means less light reaches the hypolimnion and photosynthesis there will decrease while respiration will not. In August Libby Lake has low oxygen concentrations in deep water (2-3 ppm) but anoxia does not seem to occur.

We estimated the Δ%L which would lead to complete anoxia in the hypolimnion of Big Brooklyn Lake as follows. First, we assume the hypoliminion begins at about 7m (Fig. 7) and that net photosynthesis is zero at 1% of surface illumination. If the attenuation coefficient is 0.7 m^{-1} then 1% of surface illumination will reach 7m, and about 10% will reach 3m. From Figure 1 of Tyler (1968), if 10% of surface illumination reaches 3m then the secci disc reading should be about 3-4 m. This reading is expected in a lake with surface phosphorus and chlorophyll a concentrations of about 12 μg P l^{-1} and 3 mg chl a m^{-3} (Carlson 1977; Table I). According to Figure 22c this situation is expected in Big Brooklyn Lake with a Δ%L of about 100%. We next assumed that dissolved oxygen in the hypolimnion of Big Brooklyn Lake is similar to that in Libby Lake (ca. 8 ppm). An oxygen deficit

of about 2 mg O_2 cm^{-2} mo^{-1} would reduce the hypolimnetic dissolved oxygen in Big Brooklyn to 0 ppm in about one month. Such an oxygen deficit is expected in a moderately eutrophic lake, with about 10 mg chl a m^{-3}; Chlorophyll a averaged about 15 mg m^{-3} in the hypolimnion of Libby Lake from mid July to early September (Parker 1975). Thus, assuming Libby and Big Brooklyn Lakes are fairly similar, an areal hypolimnetic oxygen deficit of 2 mg cm^{-2} mo^{-1} or more could easily occur in Big Brooklyn.

In summary we conclude that increased phosphorus loading will not affect Δ%A or TSI in Big Brooklyn Lake during the first part of the growing season (to early July). During this time rapid epilimentic flushing will prevent increases in Δ%A there. However, by August Δ%A and TSI will increase as predicted by Eq. 8b and Figure 22c. This will decrease the penetration of light and the large algal standing crop in the hypolimnion will deplete dissolved oxygen via respiration and decay. A Δ%L of about 100% should lead to a completely anoxic hypolimnion before fall turnover.

3. Little Brooklyn Lake

Little Brooklyn Lake is downstream from Big Brooklyn but has a mean depth of only 0.8m. Thermal stratification does not occur and so $\rho = \rho_f$. The hatched area of Figure 13 represents region B of Figure 23. When outflow is greater than the hatched area the lake is in region C; Δ%A and TSI will be unaffected by increased phosphorus loading. This occurs from the onset of snowmelt until early December, or throughout the whole growing season. During this time Δ%A and TSI will be unaffected by increased phosphorus loadings. If, however, increased loadings continued into early winter the lake would probably become anoxic soon after ice-on, rather than in early spring as now occurs.

4. Unnamed Lake

Unnamed Lake is shallow, does not stratify thermally, and $\rho = \rho_f$. It's volume is so small that almost any discharge places it in Region C (Fig. 14). Hence it will respond to increased phosphorus loading as does Little Brooklyn Lake.

5. Towner Lake

Towner Lake, downstream from Unnamed Lake, is morphometrically and hydrologically similar to Little Brooklyn Lake. Thus it too will respond to increased phosphorus loadings as does Little Brooklyn Lake (compare Figs. 13 and 15).

C. Summary of Management Procedures

Detailed discussions of the use of Eq. 2 in making management decisions are available elsewhere (Dillon, 1975, Dillon and Rigler 1974; Garn and Parrott 1977). A brief summary follows.

1. Choose a criterion for determining the maximum acceptable phosphorus concentration at spring overturn or $[P_{LAn}]$. Designate this value as $[P_{Max}]$. For example, decide that the lake should be relatively clear and have a secchi disc reading of at least 4m; from Carlson (1977) $[P_{Max}]$ is then 12 μg P liter^{-1}. Or if data equivalent to Figure 22 are available (less likely) determine the maximum Δ%L which will be allowed to occur; the maximum permissible phosphorus concentration is then calculated during step 2.

2. Calculate from data or estimate (see information summarized in Garn and Parrott 1977) the parameters $\bar{z}$,ρ,R and L for the lake at present. Rearrange Eq. 2 to calculate the phosphorus loading, L_{max}, which would give a value of $[P_{max}]$.

Eq. 9

$$L_{max} = \frac{[P_{max}]\bar{z}\rho}{(1-R)}$$

3. From Figure 23 and data on discharge determine those times of the year during which the lake, or its flushing layer, is in regions A, B and C (e.g. Figs 11-15).

4. Determine the allowable increase in phosphorus loading by subtracting the present loading from the maximum allowable loading (L_{max} - L).

5. Calculate the expected increase in phosphorus loading from proposed development, L_{Dev}. Garn and Parrott summarize data which can be used to do this.

6. If the lake is always in region A of Figure 23, and if $L_{Dev} > (L_{max} - L)$, then the criterion selected in step 1 will be exceeded owing to development (e.g. after development the lake would no longer be relatively clear and the secchi disk reading would be less than 4m; the maximum Δ%A chosen would be exceeded). If the lake is in region C development will affect $[P_{LAn}]$ but not Δ%A, or TSI based on secchi disk or chl a m^{-3}. This will occur regardless of the value of L_{Dev}. If the lake passes between the regions of Figure 23, then even if $L_{Dev} > (L_{max} - L)$ the affect of development on the selected criterion (i.e. Δ%A, secchi disk readings and chl a m^{-3}) will depend on the hydrologic regime (e.g. Discussion Section IVB2).

7. Make recommendations, develop alternatives, etc.

Summary

1. Data were collected to test two null hypotheses:

   H_o^1: the phosphorus mass budget model of Dillon (1975),

$$[P_{LAn}] = \frac{L(1-R)}{\bar{z}\rho}, \qquad \text{Eq. 2}$$

   does not accurately predict phosphorus concentrations in mountain lakes;

   H_o^2: it is not possible to predict what effect a given increase in phosphorus input will have on the chemical (i.e. phosphorus concentrations) and biological (i.e. phytoplankton standing crop) water quality of mountain lakes.

2. Equation 2 was rearranged to express the percent change in phosphorus concentration, $\Delta\%P$, as a function of a percent change in loading, $\Delta\%L$. Thus,

$$\Delta\%P = f\ (\Delta\%L) \qquad \text{Eq. 6}$$

   Data from algal bioassays were used to express the percent change in phytoplankton standing crop, $\Delta\%A$, as a function of $\Delta\%P$:

$$\Delta\%A = g\ (\Delta\%P) \qquad \text{Eq. 7}$$

   Equations 6 and 7 were then combined into an equation predicting the percent change in algal standing crop resulting from any percent change in phosphorus loading,

$$\Delta\%A = g[f(\Delta\%L)] \qquad \text{Eq. 8a}$$

3. Equation 2 did not accurately predict $[P_{LAn}]$ for four of the study lakes (data could not be gathered to enable predictions for the fifth lake). The only accurate prediction made by Eq. 2 was for phosphorus concentrations later in summer in the largest, deepest lake, which is most like other lakes previously used to test Eq. 2.

4. Predictions of Eq. 2 were incorrect because flushing rates for the whole lake, ρ, or the flushing layer of the lake, ρf, were very large. These large flushing rates also invalidate the predictions about $\Delta\%A$ (Eq. 8), or predictions based on Carlson's (1977) Trophic State Index (TSI). Predictions about the effect of increased phosphorus loadings on algal standing crop (i.e. on $\Delta\%A$) are affected by flushing when the latter becomes rapid enough to equal or exceed algal reproductive rates. When this occurs the relationship between phosphorus concentration or loading and water quality parameters are invalid.

5. The relations between a) $\Delta\%A$ or TSI, b) $[P_{LAn}]$, $\Delta\%P$, L or $\Delta\%L$ and c) flushing rate, ρ, are quantified for mountain lakes by Figure 23.

6. Based on the data summarized by Figure 23 H_o^1 was accepted as being valid for any lakes (mountain or otherwise) with $\rho \gtrsim 30\ yr^{-1}$, but H_o^2 was rejected. Thus increases in L should always result in increased $[P_{LAn}]$. But in rapidly flushing lakes this should not lead to increases in phytoplankton or decreases in water clarity because algal cells are washed from the lake faster than they can reproduce (i.e. the lakes are in region C of Figure 23). Three of the shallow study lakes were in this category. The flushing layer of Big Brooklyn Lake, the largest and deepest lake studied, oscillated between regions A, B and C of Figure 23. Thus during the first part of the growing season it will be little affected by increases in L. However in August $\Delta\%A$ (or TSI) would increase according to Eq. 8; a $\Delta\%L$ of about 100% should lead to completely anoxic conditions in the hypolimnion before fall turnover. East Glacier Lake, which was deeper but stratified thermally little if at all, was the only study lake which should respond to increased phosphorus loading as predicted by previously published relationships (i.e. Eqs. 2 and 8).

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Appendices

Appendix I. Data from phosphorus analyses made during the study. Phosphorus concentrations are expressed as μg P $liter^{-1}$; a (—) indicates no analysis.

	8/11/76	8/23/76	10/4/76	10/15/76	2/4/77	2/25/77	4/20/77	5/27/77	6/6/77	7/4/77
East Glacier Lake										
Inlet #1	3.4	–	–	–	–	–	–	–	–	–
#2	9.8	–	–	–	–	–	–	–	–	–
#3	9.8	9.6	–	–	–	–	–	–	–	–
#4		3.2	–	–	–	–	–	–	–	–
Outlet	8.4	19.0	4.0	6.2	–	–	–	11.6	3.4	10.0
Surface	5.6	6.0	8.6	15.2	ice	ice	ice	–	–	8.2
Meter 1	6.8	6.0	–	17.6	10.2	8.4	15.2	–	–	–
2	–	–	8.8	–	9.4	3.6	–	–	–	11.0
3	9.2	9.6	–	13.0	–	7.6	17.0	–	–	–
4	–	–	8.8	–	9.4	–	–	–	–	7.8
5	6.8	9.6	–	15.8	–	4.2	14.0	–	–	–
6	–	–	–	–	9.9	–	–	–	–	9.2
7	–	–	–	13.0	–	–	–	–	–	–

	8/26/76	8/28/76	9/29/76	1/29/77	3/2/77	4/18/77	5/27/77	6/6/77
Unnamed Lake								
Inlet #1	12.4	–	13.6	–	–	–	11.2	11.8
#2	7.8	–	–	–	–	–	–	–
Outlet	7.8	–	13.4	–	–	–	15.2	8.8
Surface	–	12.8	12.8	ice	ice	ice	–	–
Meter 1	–	12.8	16.2	23.2	38.2	27.2	–	–
2	–	12.8	15.0	–	–	26.0	–	–
2.5	–	–	15.0	–	–	–	–	–

Appendix I. (Continued)

	7/21/76	7/22/76	8/11/76	8/23/76	10/4/76	10/10/76	10/15/76
Big Brooklyn Lake							
Inlet #1	17.6	–	25.6	25.4	26.0	–	22.0
#2	12.2	–	14.8	14.8	17.4	–	–
#3	12.8	–	11.6	14.8	12.8	–	30.4
#4	–	–	12.8	23.6	12.0	–	7.2
#5	16.8	–	–	10.8	9.4	–	3.0
#6	15.0	–	11.6	20.4	22.4	–	1.75
#7	–	–	22.6	13.4	–	–	–
#8	–	4.8	4.8	8.8	5.6	–	–
#9	–	6.0	4.0	–	31.8	–	6.8
#10	–	9.2	9.0	11.0	–	–	–
#11	–	8.2	9.0	5.6	13.8	–	29.4
#12	–	9.2	8.8	55.0	10.8	–	–
#13	–	9.2	9.6	–	–	–	–
#14	–	25.0	7.8	8.2	–	–	–
#15	–	12.0	38.2	–	–	–	–
#16	–	–	8.0	–	–	–	–
Outlet	–	9.2	9.4	6.8	11.8	–	13.8
Surface	8.2	–	–	3.8	–	7.6	6.0
Meter 1	–	–	–	–	–	9.0	7.2
2	–	–	–	3.8	–	7.6	6.0
3	21.8	–	–	–	–	8.6	7.4
4	–	–	–	3.4	–	8.6	7.4
5	11.8	–	–	–	–	8.6	6.4
6	13.0	–	–	6.4	–	8.8	13.4
7	–	–	–	48.0	–	9.8–9.4	5.0
8	20.2	–	–	5.2	–	9.0–9.8	5.6
9	–	–	–	11.2	–	10.6–10.2	16.0
10	–	–	–	–	–	–	–
11	–	–	–	–	–	–	–
12	–	–	–	–	–	–	–

Big Brooklyn Lake Continued......

Appendix I. (Continued)

	2/4/77	2/25/77	4/20/77	5/27/77	6/6/77	7/4/77
Big Brooklyn Lake (Continued)						
Inlet #1	10.6	5.0	10.0	11.2	–	23.8
#2	–	–	–	–	–	17.4
#3	–	–	–	–	–	14.0
#4	–	–	–	–	–	13.4
#5	–	–	–	–	5.4	16.8
#6	–	–	–	–	6.6	14.6
#7	Only the main Inlet			–	–	–
#8	was not frozen or dry			–	–	4.2
#9	–	–	–	–	–	4.4
#10	–	–	–	–	–	7.4
#11	–	–	–	–	17.6	17.4
#12	–	–	–	–	14.6	–
#13	–	–	–	–	–	–
#14	–	–	–	–	9.8	–
#15	–	–	–	–	–	–
#16	–	–	–	–	–	–
Outlet	9.4	2.4	9.6	10.2	6.6	–
Surface	ice	ice	ice	–	–	12.6
Meter 1	14.2	7.2	18.0	–	–	–
2	–	–	–	–	–	11.6
3	12.6	3.4	11.0	–	–	–
4	–	–	–	–	–	17.0
5	9.4	2.2	–	–	–	–
6	–	–	12.8	–	–	14.0
7	–	2.4	–	–	–	–
8	9.4	–	–	–	–	17.2
9	–	6.6	11.6	–	–	–
10	–	–	–	–	–	–
11	–	6.6	–	–	–	–
12	11.4	–	20.4	–	–	–

Appendix I. (Continued)

	7/27/76	8/26/76	9/29/76	1/29/77	4/18/77	5/27/77	6/6/77
Towner Lake							
Inlet #1	16.4	12.4	9.6	36.2	–	14.6	–
#2	11.0	13.0	–	–	–	–	–
#3	–	–	–	–	–	–	–
#4	6.6	6.2	–	–	–	–	–
Outlet	15.4	7.2	11.9	37.2	–	14.6	7.8
Surface	16.0	11.0	7.2	ice	ice	ice	–
Meter 1	–	13.8	9.2	18.8	180.0	–	–
1.5	–	13.8	9.8	–	172.4	–	–
2	16.8	–	–	–	–	–	–
3	–	–	–	–	–	–	–

	7/11/76	7/29/76	7/11/76	8/26/76	8/28/76	10/1/76	1/29/77	3/2/77	4/20/77	5/27/77	6/6/77
Little Brooklyn Lake											
Inlet #1	11.0	15.0	7.2	7.4	–	9.8	23.8	–	8.6	17.2	–
#2	10.2	16.6	11.6	12.2	–	7.6	–	–	–	–	8.6
#3	10.0	6.4	7.8	–	–	–	–	–	–	–	7.0
#4	19.0	12.8	11.0	7.8	–	15.2	–	–	–	–	7.0
#5	–	10.4	6.6	24.8	–	–	–	–	–	–	–
Outlet	10.2	–	9.6	10.8	–	8.6	5.6	–	7.6	15.0	–
Surface	10.4	11.2	–	–	11.2	11.0	ice	ice	ice	–	–
Meter 1	–	23.2	–	–	11.2	8.0	22.6	13.7	176.6	–	–
2	–	11.2	–	–	10.2	9.0	–	–	–	–	–
3	–	–	–	–	–	–	–	–	–	–	–

Appendix II. Data from volume flow measurements made during the study. Volume flow is expressed as $m^3 sec^{-1}$; a (-) indicates no measurement made; a(*) indicates the flow was too small to measure with the Pygmy current meter.

	7/29/76	8/21/76	5/31/77	6/18/77
East Glacier Lake				
Inlet #1	*	*	*	*
#2	*	*	*	*
#3	*	*	*	*
#4	*	*	*	*
Outlet	.01	.04	.009	.05

	7/21/76	7/22/76	7/29/76	8/21/76	10/4/76	10/15/76	2/4/77	4/18/77	5/31/77	6/18/77
Big Brooklyn Lake										
Inlet #1	*	–	*	*	*	*	0	0	0	*
#2	*	–	*	*	*	0	0	0	0	*
#3	*	–	*	*	*	*	0	0	0	*
#4	*	–	*	*	.003	*	0	0	0	*
#5	.03	–	.01	.008	.006	.005	.002	.0007	.03	.04
#6	*	–	*	*	*	*	0	0	0	*
#7	*	–	*	*	*	*	0	0	0	*
#8	*	–	*	*	*	*	0	0	0	*
#9	.001	–	*	*	.001	.002	0	0	*	*
#10	.01	–	.002	.005	*	*	0	0	*	.02
#11	.05	–	.04	.03	.01	.002	0	0	*	.04
#12	*	–	*	*	*	0	0	0	0	*
#13	.01	–	*	*	*	0	0	0	0	*
#14	*	–	*	*	*	0	0	0	0	*
#15	*	–	*	*	*	0	0	0	0	*
#16	*	–	*	*	*	*	0	0	0	*
Outlet	–	.15	.07	.05	.02	–	–	–	.09	.26

Appendix II. (Continued)

	7/8/76	7/11/76	7/16/76	7/29/76	8/14/76	8/21/76	10/1/76	1/28/77	4/18/77	5/31/77	6/18/77
Little Brooklyn Lake											
Inlet #1	.30	.28	.17	–	.09	.07	.04	*	.0007	.17	.39
#2	.04	.05	.05	–	∿.00002	*	.0004	0	0	.02	.04
#3	–	.002	.006	–	*	0	0	0	0	*	.02
#4	–	.02	.007	–	.005	*	0	0	0	*	.01
#5	–	–	–	–	.005	*	0	0	0	*	*
Outlet	.38	.36	.27	.13	.08	.06	.05	.04	.02	.18	.32

	8/26/76	8/28/76	9/29/76	5/27/77	6/18/77
Unnamed Lake					
Inlet #1	.04	.03	.02	.05	.22
#2	*	*	*	*	*
Outlet	.04	.03	.01	.08	.21

	7/26/76	8/26/76	10/1/76	1/29/77	5/27/77	6/19/77
Towner Lake						
Inlet #1	.26	.05	.04	*	.14	.33
#2	*	*	*	*	*	*
#3	*	*	*	*	*	*
#4	*	*	*	*	*	*
Outlet	.25	.06	.02	.007	.17	.54

Appendix III. The average number of cells ml^{-1}, plus and minus one standard deviation, for each treatment during the course of the May bioassay of water from Towner Lake. The following abbreviations are used: Cul, culture medium: LW, autoclaved lake water; -P, phosphorus not added when preparing the culture medium; +P, the indicated g P $liter^{-1}$ added to the treatment; -N, nitrogen not added when preparing the culture medium; +N, the indicated g N $liter^{-1}$ added to the treatment.

Sample	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15	Day 18
Cul	61,250	275,000 ±75,498	1,923,750 ±989,784	4,037,500 ±1,569,833	3,718,750 ±1,462,500	4,850,000 ±1,296,791	4,637,500 ±1,133,854
Cul -P	61,250	62,500 ±25,000	61,250 ±17,017	41,250 ±13,150	52,500 ±29,861	31,250 ±10,308	
Cul -N	61,250	70,000 ±35,590	115,000 ±33,416	95,000 ±19,579	98,750 ±24,958	60,000 ±8,165	
Cul -P -N	61,250	85,000 ±40,415	65,000 ±20,412	42,500 ±8,660	47,500 ±6,455	57,500 ±22,174	
Cul -P +5	61,250	250,000 ±29,439	93,750 ±2,660	33,750 ±7,500	55,000 ±17,795	62,500 ±20,616	65,000 ±19,149
Cul -P +20	61,250	82,500 ±23,629	418,750 ±67,992	413,750 ±55,883	335,000 ±61,779	391,250 ±150,575	490,000 ±162,686
Cul -P +50	61,250	150,000 ±21,603	987,500 ±47,871	935,000 ±42,622	818,750 ±143,433	1,487,500 ±217,467	1,132,500 ±276,089
Cul -N +35	61,250	135,000 ±23,805	135,250 ±43,208	136,250 ±30,380	123,750 ±29,545	190,000 ±58,166	185,000 ±49,498

Appendix III. (Continued)

Sample	Day 1	Day 4	Day 7	Day 10	Day 13	Day 18
Cul -N +140	61,250	203,750 ±23,229	255,000 ±68,557	320,000 ±40,208	282,500 ±41,130	310,000 ±38,514
Cul -N +350	61,250	485,000 ±219,279	992,500 ±149,750	972,500 ±386,792	1,150,000 ±201,039	903,750 ±153,209
Cul -N -P +35 +5	61,250	66,250 ±18,875	70,000 ±8,165	58,750 ±20,565	47,500 ±9,574	57,500 ±27,538
Cul -N -P +140 +20	61,250	100,000 ±7,071	215,000 ±92,556	203,750 ±43,851	245,000 ±70,475	212,500 ±15,000
Cul -N -P +350 +50	61,250	97,500 ±33,292	597,500 ±118,989	585,000 ±52,281	75,250 ±269,548	615,000 ±285,716
LW	61,250	52,500 ±17,559	67,500 ±37,749	70,000 ±17,321	52,500 ±26,300	
LW +P5	61,250	140,000 ±23,452	235,000 ±142,945	156,250 ±38,595	182,500 ±68,981	
LW +P20	61,250	216,250 ±22,867	275,000 ±112,101	191,250 ±46,615	242,500 ±70,415	

Appendix III. (Continued)

Sample	Day 1	Day 5	Day 8	Day 11	Day 14	Day 18
LW +P50	61,250	227,500 ±27,538	200,000 ±58,737	326,250 ±105,307	313,750 ±86,927	
LW +N35	61,250	42,500 ±9,574	70,000 ±24,833	87,500 ±33,040	58,750 ±14,930	
LW +N140	61,250	55,000 ±20,817	53,750 ±18,875	65,000 ±31,091	48,750 ±28,395	
LW +N350	61,250	42,500 ±12,583	35,000 ±10,801	63,500 ±27,538	36,250 ±14,930	
LW +P5 +N35	61,250	107,500 ±25,000	127,500 ±52,361	162,500 ±42,720	191,250 ±74,316	118,750 ±44,791
LW +P20 +N140	61,250	277,500 ±138,654	361,250 ±37,500	477,500 ±161,323	221,250 ±65,749	283,750 ±18,875
LW +P50 +N350	53,750	1,102,500 ±110,868	892,500 ±159,661	1,187,500 ±201,556	830,000 ±203,756	900,000 ±158,114

Appendix IV. The average number of cells ml^{-1}, plus and minus one standard deviation, for each treatment during the course of the August bioassay of water from Towner Lake. For explanation of abbreviations, see Appendix III.

Sample	Day 1	Day 3	Day 5	Day 11	Day 18	Day 24
Cul	28,125	450,000 ±75,388	2,637,500 ±1,041,133	3,787,500 ±1,245,910	3,537,500 ±526,585	3,775,000 ±1,133,211
Cul -P	28,125	32,500 ±18,930	40,000 ±16,330	35,000 ±5,774	30,000 ±16,330	17,500 ±9,574
Cul -N	28,125	166,250 ±16,520	145,000 ±38,730	170,000 ±27,080	200,000 ±29,439	167,500 ±42,720
Cul -P -N	28,125	37,500 ±9,574	45,000 ±12,910	47,500 ±20,616	45,000 ±12,910	42,500 ±15,000
Cul -P +5	28,125	122,500 ±35,940	140,000 ±61,644	105,000 ±31,091	162,500 ±37,749	105,000 ±37,859
Cul -P +20	28,125	403,750 ±69,086	587,500 ±132,256	600,000 ±177,951	637,500 ±103,078	542,500 ±165,806
Cul -P +50	28,125	558,750 ±163,216	1,875,000 ±451,848	1,887,500 ±337,577	2,087,500 ±213,600	1,775,000 ±119,024
Cul -N +35	28.125	260,000 ±85,440	255,000 ±38,730	170,000 ±39,158	237,500 ±96,738	240,000 ±94,163

Appendix IV. (Continued)

Sample	Day 1	Day 4	Day 6	Day 13	Day 19	Day 25
Cul -N +140	28,125	475,000 ±63,246	477,500 ±71,356	552,500 ±204,512	497,500 ±108,743	545,000 ±140,594
Cul -N +350	28,125	692,500 ±87,797	825,000 ±208,726	792,500 ±302,476	762,500 ±159,661	975,000 ±322,749
Cul -N -P +35 +5	28,125	132,500 ±45,185	102,500 ±33,040	142,500 ±23,629	90,000 ±14,142	132,500 ±9,574
Cul -N -P +140 +20	36,250	515,000 ±57,446	467,500 ±94,648	520,000 ±100,995	472,500 ±105,000	667,500 ±122,031
Cul -N -P +350 +50	36,250	915,000 ±23,805	1,312,500 ±404,918	800,000 ±120,277	837,500 ±199,395	850,000 ±248,328
LW	36,250	417,500 ±65,128	455,000 ±122,882	697,500 ±200,229	575,000 ±104,722	587,500 ±66,144
LW +P5	36,250	432,500 ±75,774	467,500 ±129,711	517,500 ±104,363	602,500 ±135,247	595,000 ±144,799
LW +P20	36,250	552,500 ±26,300	677,500 ±283,593	660,000 ±100,333	715,000 ±109,087	688,750 ±240,914

Appendix IV. (Continued)

Sample	Day 1	Day 10	Day 17	Day 21	Day 27
LW +P50	36,250	646,667 ±5,774	700,000 ±147,986	1,116,600 ±236,291	770,000 ±199,750
LW +N35	36,250	750,000 ±158,114	800,000 ±101,653	720,000 ±135,401	800,000 ±81,650
LW +N140	36,250	821,250 ±113,899	765,000 ±94,692	665,000 ±147,083	832,500 ±138,894
LW +N350	32,500	1,227,500 ±566,591	1,165,000 ±244,745	986,250 ±127,892	1,500,000 ±380,789
LW +P5 +N35	32,500	736,250 ±194,138	767,500 ±57,373	635,000 ±95,743	687,500 ±151,959
LW +P20 +N140	32,500	993,750 ±319,097	900,000 ±115,470	703,750 ±125,391	806,250 ±116,145
LW +P50 +N350	32,500	1,800,000 ±264,575	1,537,500 ±143,614	1,643,750 ±157,288	1,637,500 ±228,674

Appendix V. The average number of cells ml^{-1}, plus and minus one standard deviation, for each treatment during the course of the March bioassay of water from Big Brooklyn Lake. For explanation of abbreviations, see Appendix III.

Sample	Day 1	Day 3	Day 9	Day 12	Day 15	Day 18
Cul	37,500	106,075 ±30,920	216,750 ±30,223	2,762,500 ±335,721	2,843,750 ±352,595	2,831,250 ±190,804
Cul -P	37,500	66,975 ±13,782	50,278 ±14,269	65,000 ±17,321	60,000 ±10,801	86,250 ±8,539
Cul -N	37,500	63,300 ±6,700	75,000 ±7,876	93,333 ±10,408	93,333 ±15,275	80,000 ±43,589
Cul -P -N	37,500	64,975 ±19,712	66,389 ±14,993	70,000 ±30,822	62,500 ±6,455	57,500 ±15,546
Cul -P +5	37,500	22,475 ±7,395	28,806 ±3,811		17,500 ±8,660	10,000 ±7,071
Cul -P +20	37,500	34,150 ±31,564	92,750 ±30,336	132,500 ±23,274	147,500 ±69,462	167,500 ±85,684
Cul -P +50	37,500	27,775 ±9,196	17,222 ±4,231	130,000 ±71,531	443,750 ±147,387	546,250 ±132,814
Cul -N +35	37,500	68,250 ±30,966	49,444 ±5,300	88,750 ±17,017	118,750 ±77,929	61,250 ±11,087

Appendix V. (Continued)

Sample	Day 21	Day 24	Day 27	Day 30	Day 33
Cul	3,187,500	2,462,500	2,437,500	3,175,000	2,825,000
	±1,646,524	±278,014	±444,644	±742,181	±733,144
Cul -P	107,500	70,000	103,750	90,000	117,500
	±6,455	±24,833	±13,150	±27,080	±29,861
Cul -N	92,500	111,667	83,333	110,000	83,333
	±51,881	±42,525	±18,930	±36,056	±15,275
Cul -P -N	55,000	80,000	68,750	60,000	67,500
	±14,720	±14,720	±17,017	±20,000	±30,957
Cul -P +5	9,125	18,750	25,000	17,500	17,500
	±1,750	±17,970	±12,247	±9,574	±5,000
Cul -P +20	111,250	161,250	137,500	152,500	107,500
	±96,036	±73,979	±66,018	±51,235	±75,443
Cul -P +50	565,000	610,000	590,000	652,500	692,500
	±108,244	±84,063	±100,582	±98,107	±90,692
Cul -N +35	61,250	110,000	92,500	62,500	87,500
	±8,539	±24,495	±9,574	±17,078	±9,574

Appendix V. (Continued)

Sample	Day 1	Day 4	Day 10	Day 13	Day 16	Day 19
Cul -N +140	37,500	46,625 ±30,673		115,000 ±23,452		101,250 ±22,867
Cul -N +350	37,500	78,300 ±24,425		527,500 ±55,151		613,750 ±154,239
Cul -N -P +35 +5	31,000	80,800 ±38,144				62,500 ±11,902
Cul -P -N +140 +20	31,000	33,275 ±11,906				108,750 ±34,731
Cul -P -N +350 +50	31,000	59,125 ±23,160			298,750 ±136,405	352,500 ±15,546
LW	31,000	53,025 ±8,805	70,000 ±14,142			78,333 ±20,817
LW +P5	31,000	53,850 ±8,719	63,250 ±51,273			83,750 ±9,465
LW +P20	31,000	53,550 ±14,251	77,500 ±18,484			81,250 ±11,087

Appendix V. (Continued)

Sample	Day 22	Day 25	Day 28	Day 31	Day 34
Cul -N +140	131,250	123,750	145,000	163,750	
	±22,867	±20,966	±27,080	±28,687	
Cul -N +350	552,500	506,250	481,250	512,250	
	±85,391	±129,703	±73,640	±48,856	
Cul -N -P +35 +5	76,250	77,500	61,250	56,250	
	±7,500	±27,234	±16,520	±20,156	
Cul -P -N +140 +20	92,500	82,500	70,000	81,250	
	±6,455	±21,016	±24,495	±24,958	
Cul -P -N +350 +50	655,000	543,750	675,000	468,750	
	±84,261	±62,500	±35,355	±110,633	
LW	101,667	75,000	80,000	80,000	76,250
	±28,431	±5,000	±10,000	±5,000	±14,361
LW +P5	103,750	82,500	81,250	76,250	87,500
	±6,292	±20,207	±22,127	±26,575	±15,000
LW +P20	105,000	110,000	85,000	65,000	98,750
	±18,708	±76,920	±24,833	±22,730	±11,087

Appendix V. (Continued)

Sample	Day 1	Day 4	Day 11	Day 14	Day 17	Day 20
LW +P50	31,000	50,800 ±9,219	110,000 ±15,811		90,000 ±54,160	72,500 ±29,861
LW +N35	31,000	47,425 ±14,410	76,250 ±13,150		63,750 ±13,769	
LW +N140	31,000	80,525 ±8,152			95,000 ±43,205	
LW +N350	30,500	54,125 ±17,182	95,000 ±14,720		96,250 ±19,311	
LW +P5 +N35	30,500	64,125 ±21,059	72,500 ±15,546	200,000 ±31,358	77,500 ±15,000	62,500 ±8,660
LW +P20 +N140	30,500	43,850 ±10,182	117,500 ±15,546	398,750 ±71,691	146,250 ±17,017	96,250 ±17,970
LW +P50 +N350	30,500	67,450 ±9,049	292,500 ±93,853	418,750 ±189,269	327,500 ±68,007	168,750 ±26,260

Appendix V. (Continued)

Sample	Day 23	Day 26	Day 29	Day 32	Day 35
LW +P50	127,500 ±25,331	70,000 ±16,330	105,000 ±23,805	112,500 ±15,000	81,250 ±14,930
LW +N35	71,250 ±21,360	72,500 ±22,174	77,500 ±28,723	77,500 ±8,660	67,500 ±13,229
LW +N140	83,750 ±16,008	90,000 ±20,000	105,000 ±25,166	112,500 ±19,365	124,500 ±24,173
LW +N350	77,500 ±27,234	122,500 ±54,391	91,250 ±8,539	138,750 ±24,622	292,500 ±93,140
LW +P5 +N35	95,000 ±14,720	92,500 ±26,300	92,500 ±9,574	120,000 ±8,165	
LW +P20 +N140	178,750 ±23,229	155,000 ±36,968	182,500 ±29,861	188,750 ±17,500	
LW +P50 +N350	402,500 ±85,684	320,000 ±87,560	327,500 ±56,199	386,250 ±136,649	

Appendix VI. The average number of cells ml^{-1}, plus and minus one standard deviation, for each treatment during the course of the July bioassay of water from Big Brooklyn Lake. For explanation of abbreviations, see Appendix III.

Sample	Day 1	Day 4	Day 6	Day 9	Day 12
Cul	104,375	910,000 ±561,234	3,893,750 ±846,654	3,418,750 ±354,950	3,825,000 ±679,461
Cul -P	104,375	62,500 ±30,957	105,000 ±23,452	80,000 ±17,795	70,000 ±10,801
Cul -N	104,375	531,250 ±201,469	442,500 ±86,843	356,250 ±143,723	326,250 ±53,600
Cul -P -N	104,375	101,250 ±14,361	128,750 ±23,936	105,000 ±17,795	82,500 ±20,616
Cul -P +5	49,531	71,250 ±35,678	81,250 ±13,150	60,000 ±14,720	85,000 ±30,277
Cul -P +20	31,250	492,500 ±78,899	442,500 ±87,607	500,000 ±73,598	452,500 ±52,361
Cul -P +50	31,250	1,450,000 ±703,562	1,425,000 ±117,260	1,418,750 ±162,500	1,293,750 ±96,555
Cul -N +35	31,250	255,000 ±95,743	270,000 ±37,193	273,750 ±23,585	280,000 ±24,833

Appendix VI. (Continued)

Sample	Day 1	Day 5	Day 7	Day 10	Day 13
Cul -N +140	31,250	438,750 ±44,230	437,500 ±40,517	457,500 ±95,699	507,500 ±59,512
Cul -N +350	26,250	975,000 ±86,603	1,218,750 ±85,086	1,262,500 ±216,506	1,193,750 ±154,616
Cul -N -P +35 +5	26,250	105,000 ±34,881	80,000 ±35,590	93,750 ±35,678	96,250 ±38,379
Cul -N -P +140 +20	26,250	336,250 ±29,545	445,000 ±36,968	410,000 ±94,428	443,750 ±54,524
Cul -N -P +350 +50	18,750	1,170,000 ±182,392	1,012,500 ±25,000	1,100,000 ±226,385	1,268,750 ±155,958
LW	20,625	125,000 ±20,817	132,500 ±30,957	157,500 ±30,957	145,000 ±53,229
LW +P5	18,750	130,000 ±32,404	110,000 ±38,297	152,500 ±61,847	195,000 ±82,664
LW +P20	18,750	120,000 ±22,730	117,500 ±29,861	147,500 ±18,930	150,000 ±20,000

Appendix VI. (Continued)

Sample	Day 1	Day 8	Day 11	Day 14
LW +P50	18,750	132,500 ±17,078	133,750 ±52,658	127,500 ±44,064
LW +N35	18,750	97,500 ±25,000	106,250 ±41,508	128,750 ±25,617
LW +N140	18,750	107,500 ±42,720	92,500 ±20,207	83,750 ±24,622
LW +N350	18,750	112,500 ±25,000	108,750 ±19,311	106,250 ±9,465
LW +P5 +N35	18,750	127,500 ±57,373	115,000 ±43,780	137,500 ±37,969
LW +P20 +N140	18,750	280,000 ±49,666	318,750 ±45,162	336,250 ±93,039
LW +P50 +N350	18,750	787,500 ±172,506	693,750 ±136,099	806,250 ±159,915

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
Rocky Mountain Forest and Range Experiment Station
South Dakota School of Mines Campus
Rapid City, South Dakota 57701

REPLY TO: 4040 Cooperation

November 30, 1977

SUBJECT: Eisenhower Consortium Contract No. 16-586-GR, EC#196

TO: Dr. Gordon Lewis

Enclosed please find a copy of final report for Eisenhower Consortium Contract Number 16-586-GR, EC#196 with the University of Wyoming and a copy of Dr. Parker's cover letter.

Ardell J. Bjugstad

ARDELL J. BJUGSTAD
Project Leader

Enclosures

ENT OF ZOOLOGY AND PHYSIOLOGY

TELEPHONE: (307) 766-4207

THE UNIVERSITY OF WYOMING
UNIVERSITY STATION, BOX 3166
LARAMIE, WYOMING 82071

November 8, 1977

Dr. Ardell Bjugstad
Forestry Resources Laboratory
South Dakota School of Mines
Rapid City, SD 57701

Dear Ardell:

You will receive under separate cover five copies of the final report for Eisenhower Consortium, contract number 16-586-GR, EC#196 with the University of Wyoming. The report is overdue by about three months. For this I apologize, but hasten to provide an explanation. I myself received no salary from the contract, and the graduate students working on the study were paid only through May, 1977. Despite this they continued to collect and analyze data through August on their own time. September was hectic, frustrating and exciting; with all data finally analyzed qualitative patterns emerged, but much thinking and discussion occurred before we were able to quantitate them (e.g. Figure 23 of the report). However, as a result we conclude that procedures recommended and used by the Forest Service for evaluating the effect of development on lakes are inapplicable to many or most of the lakes in the Snowy Range. This must also be true for any rapidly flushing lake regardless of its geographic location. Hence we hope that although we are tardy in submitting it, our report will be of practical use for the Forest Service. We plan to rewrite and submit the report for journal publication, and will request an Eisenhower Consortium journal number at the appropriate time.

Finally I - actually, all three of us - appreciate the confidence shown in us by the award of the contract. As always there were difficult times, but hopefully something useful resulted from our work and by-and-large we had a ball performing it.

Yours very truly,

Mike

Michael Parker
Associate Professor of Zoology

MP:cf

Rapid City RWU
Rec'd NOV 14 1977
PC'd ....
P. Ldr. ✓ AB
Adm.O. ....
Hyd. ....
Sil. ....
Rng. ....
Aq.B. ✓ CH
Geo. ....
Hyd. ....
F&WS ....
Sup.T. ....
Rng.T. ....
Bio.T. ....
Lab.T. ....
Chem.T. ....
Adm.C. ✓ file
Clk.T ....